Naval Research Laboratory
Stennis Space Center, MS 39529-5004

NRL/MR/7431--95-7595

Coastal Benthic Boundary Layer Special Research Program: A Review of the Second Year

Michael D. Richardson

Seafloor Sciences Branch
Marine Geosciences Division

July 24, 1995

REPORT DOCUMENTATION PAGE

Form Approved
OBM No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 24, 1995	Final

4. TITLE AND SUBTITLE

Coastal Benthic Boundary Layer Special Research Program:
A Review of the Second Year

5. FUNDING NUMBERS

Job Order No.	574525805
Program Element No.	0601153N
Project No.	R3103
Task No.	000
Accession No.	DN252025

6. AUTHOR(S)

Michael D. Richardson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Marine Geosciences Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/7431--95-7595

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
Dr. Fred Saafeld, Code 01
Ballston Centre Tower One
800 N. Quincy Street
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Coastal Benthic Boundary Layer Special Research Program (CBBLSRP) is a 5-year Office of Naval Research program that addresses the physical characterization and modeling of benthic boundary layer processes and the impact of these processes on seafloor structure, properties, and behavior. In this report, results from 2 years of experiments are summarized. These experiments were conducted on the soft methane-rich sediments of Eckernförde Bay (Baltic Sea) and on the sandy relict sediments of the northeastern Gulf of Mexico. Year-end reports for the 23 projects supported by the CBBLSRP are included along with a summary of the first 2 years' accomplishments. A list of publications supported by the CBBLSRP is included.

14. SUBJECT TERMS

acoustics, sediments, mines

15. NUMBER OF PAGES

276

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

CONTENTS

COASTAL BENTHIC BOUNDARY LAYER SPECIAL RESEARCH PROGRAM:

A REVIEW OF THE SECOND YEAR

1.0 INTRODUCTION

The Coastal Benthic Boundary Layer Special Research Program (CBBLSRP) is a 5-year Office of Naval Research (ONR) program that addresses physical characterization and modeling of benthic boundary layer processes and the impact these processes have on seafloor properties that affect shallow-water naval operations. Four workshops were convened between November 1991 and February 1992 to establish program direction (Richardson, 1992). Based on workshop recommendations, research was focused on modeling the effects benthic boundary layer processes have on sediment structure, properties and behavior (Figure 1). Sediment physical structure provides the common perspective to: a) quantitatively model relationships among sediment physical, acoustic, electrical, and rheological (mechanical) properties; b) quantify the effects of environmental processes on the spatial and temporal distribution of sediment properties; and c) model sediment behavior (acoustic, electrical, and mechanical) under direct and remote stress.

A basic understanding of the physical relationships among processes and properties will contribute to development of realistic models of: sediment strength, stability, and transport; sediment stress-strain relationships in cohesive and non cohesive sediments; dynamic seabed-structure interactions; animal-sediment interactions; high-frequency acoustic scattering phenomena; and propagation of high-frequency acoustic energy into and through poro-elastic media. Predictive models developed through this program should enhance MCM technological capabilities in several important areas, including: acoustic and magnetic detection, classification, and neutralization of proud and buried mines; shock wave propagation; prediction of mine burial; and sediment classification.

Quantitative physical models are being tested by a series of field experiments at coastal locations where differing environmental processes determine sediment structure (Richardson, 1993, 1994). Participating investigators are supported by 23 CBBLSRP projects and eight related projects supported by FWG, University of Kiel and NRL (Table 1). The first experiment was a joint United States (NRL and CBBLSRP) and German (FWG and University of Kiel) study of the gas-rich muds of Eckernförde Bay in the Baltic Sea. At this site biogeochemical processes are responsible for the formation of subsurface methane gas bubbles that significantly affect sediment structure, behavior, and properties. The second experiment was conducted on the West Florida Sand Sheet, southeast of Panama City, Florida. Sediments are a mixture of clastic sands and shells which are reworked by wave-current action (hydrodynamic processes). Joint NRL/FWG experiments were also conducted in a carbonate environment (Florida Keys during February 1995) where biogeochemical diagenetic processes, such as sediment mineralization, dissolution and cementation, control sediment structure. The Key West experiments will be included in next years review. Further experiments are planned for a benthic environment where

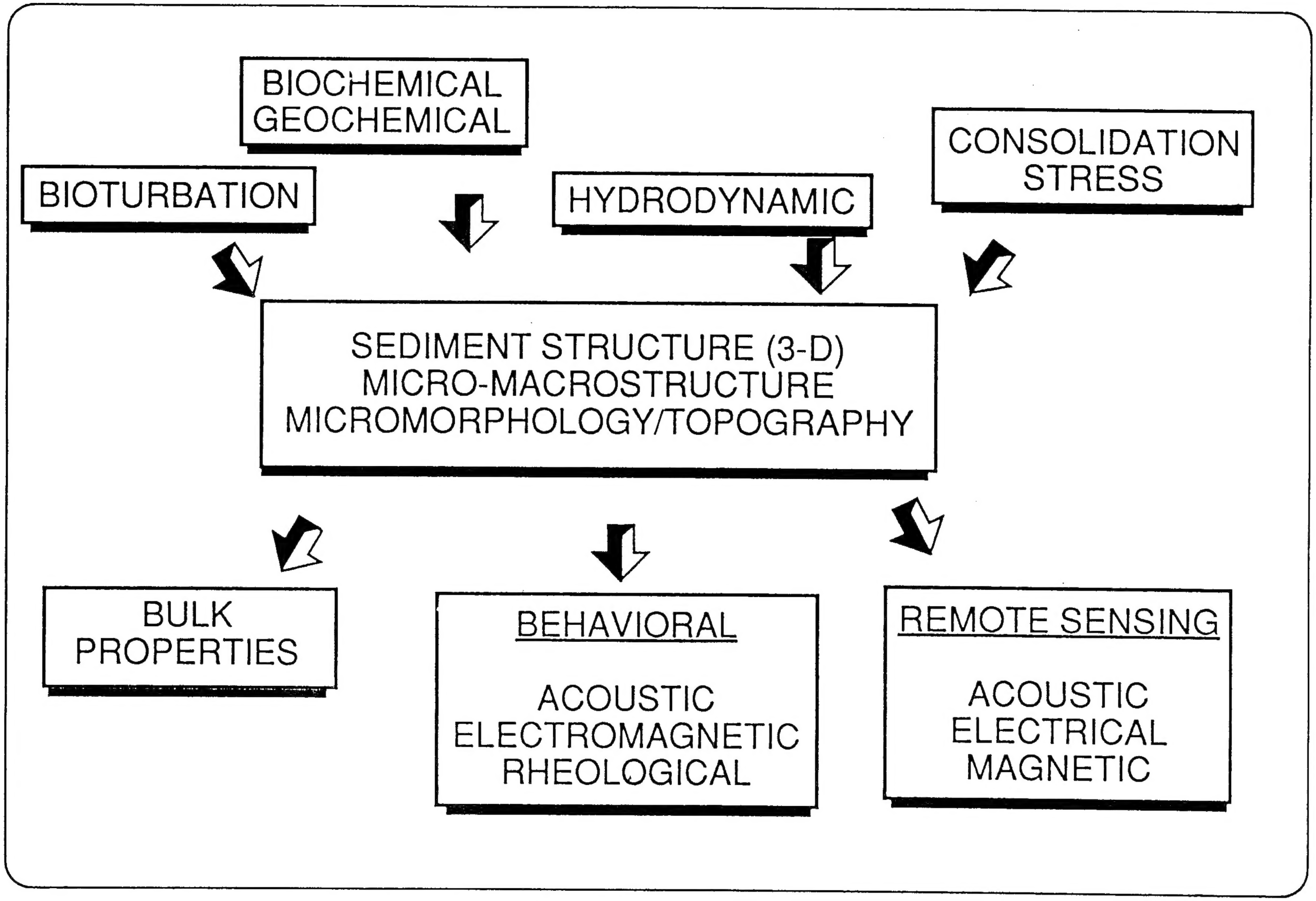


Figure 1. Schematic depiction of CBBLSRP Program direction.

Table 1. Coastal Benthic Boundary Layer Research Projects and Contributing Projects Supported by NRL and FWG (FY95)

Measurement and description of the upper seafloor sub-decimeter heterogeneity for macrostructure geoacoustic modeling (Texas A&M) • *A.L. Anderson*

Sediment properties from grain and macrofabric measurement (NRL, University of New Orleans, and Resource Dynamics) • *R.H. Bennett, Dennis Lavoie, R.J. Baerwald, and M.H. Hulbert*

High-frequency acoustic scattering from sediment roughness and sediment volume inhomogeneities (NRL) • *K.B. Briggs*

Processes of macro scale volume inhomogeneity in the benthic boundary layer (Texas A&M) • *W.A. Bryant and N.C. Slowey*

Analysis of data from in-situ acoustic scattering experiments (University of Texas) • *N.P. Chotiros*

New geophysical technologies applied to the quantitative evaluation of seabed properties related to mine burial prediction (UCNW) • *A.M. Davis*

Analysis of the rheological properties of nearbed (fluid mud) suspensions occurring in coastal environments (Lafayette College) • *R.W. Faas*

Characterization of surficial roughness and subbottom inhomogeneities from seismic data analysis (Woods Hole Oceanographic Institution) • *D.J. Tang, G.V. Frisk and T.K. Stanton*

Statistical characterization of the benthic boundary for broadband acoustic scattering (Penn State) • *K.E. Gilbert, T.J. Kulbago*

Measurement of high-frequency acoustic scattering from coastal sediments (University of Washington) • *D.R. Jackson and K.L. Williams*

Electrical resistivity imaging of unconsolidated sediments (BGS) • *P.D. Jackson*

Structural analysis of marine sediment microfabric (Quest Integrated, Inc.) • *J.J. Kolle and A.C. Mueller*

Qualification of high frequency acoustic response to seafloor micromorphology in shallow water (NRL) • *D.N. Lambert and J.A. Hawkins*

Measurement of shear modulus in-situ and in the laboratory (NRL) • *Dawn Lavoie and A. Pittenger*

Quantification of gas bubbles and dissolved gas sources and concentrations in organic-rich, muddy sediments (University of North Carolina at Chapel Hill) • *C.S. Martens and D. Albert*

Physical and biological mechanisms influencing the development and evolution of sediment structure (State University of New York and Virginia Institute of Marines Science) • *C.A. Nittrouer, L.D. Wright, G. Lopez and C. Friedrichs*

The detection of continuous impedance structures using full spectrum sonars (Florida Atlantic University) • *S.G. Schock and L.R. LeBlanc*

Variability of seabed sediment microstructure and stress-strain-time behavior in relation to acoustic characterization (University of Rhode Island) • *A.J. Silva, M. Sadd, G.E. Veyera and H. Brandes*

High-resolution bottom backscattering measurements (NRL) • *S. Stanic*

Experimental and theoretical studies of near-bottom sediments to determine geoacoustic and geotechnical properties (Lamont-Doherty) • *R.D. Stoll*

Image analysis of acoustic texture: A rapid predictor of physical and acoustic properties of unconsolidated marine sediments and processes affecting their relationships (NRL) • *D.K. Young, R.J. Holyer and J.C. Sandidge*

The relationship between high-frequency acoustic scattering and seafloor structure (University of Southern Mississippi) • *Li Zhang*

NRL Projects Providing CBBL Support

In-situ surficial sediment geoacoustic properties • *M.D. Richardson*
High-frequency acoustics and environmental physics for mine countermeasures • *S. Stanic*
Sediment geochemical processes • *K.M. Fischer*
MCM Tactical Environmental Data System: Acoustic seafloor classification technology • *D.N. Lambert and D.J. Walter*
Ambient and dynamic pore pressures • *R.H. Bennett*

Other Projects Providing Support

Measurement of bottom backscattering strength with digital side scan sonar (FWG) • *I.H. Stender, H. Fiedler and G. Fechner*
Investigation of gas content in marine sediments (University of Kiel) • *F. Abegg and R. Koester*
In-situ physical properties of marine sediments (University of Kiel) - *F. Theilen*
Acoustic Lance operations in Eckernförde Bay (University of Hawaii) *R.H. Wilkens, S.S. Fu and L.W. Frazer*

biological processes, such as bioturbation, exert the major influence on near-surface structure. The goal of the CBBLSRP is to provide physical models that predict sediment structure and behavior from knowledge of environmental processes for each environment.

1.1 DESCRIPTION OF THE ECKERNFÖRDE BAY EXPERIMENTS

Five joint US/German cruises investigating gassy sediments of Eckernförde Bay (Baltic Sea) have been completed. The first cruise, aboard the WFS Planet (1-20 February, 1993), was a survey of potential study sites. Sediments were characterized by remote acoustic methods (side-scan, narrow-beam normal-incident, and FM-chirp sonars) and direct sediment sampling with gravity and box cores. A 1.0-x-2.3-km area with uniform sediment was chosen for further study. Sediments at the study site are recently deposited soft muds, with high water contents and very low shear strengths. Remote acoustic measurements suggested methane bubbles were present as shallow as 0.5 to 0.7 m below the sediment-water interface. The existence of gas bubbles in sediments was confirmed by CT-scans of pressurized core samples. On the second cruise, also aboard the WFS Planet (29 March to 3 April 1993), acoustic and environmental towers were deployed to monitor long-term changes in high-frequency bottom scattering, benthic boundary layer hydrodynamic processes (bed stress from bottom currents), and sediment transport processes (turbidity from photographs and optical backscatterance sensors). Box core samples were collected to characterize benthic community structure, depths and rates of sediment reworking, and sediment properties.

The main experiment (20 April to 5 June 1993) included 80 scientists, engineers and technicians from 18 research organizations. Support from FWG, WTD-71, the German Navy, and the Institute of Geology and Paleontology University of Kiel consisted of seven ships, a navy dive team, student assistance, sampling equipment, navigation, a recompression chamber, laboratory space, customs assistance, and numerous other shore-based logistic support activities. The NRL contingent (9 projects; 25 NRL scientists and engineers) concentrated on acoustic bottom scattering and propagation studies; sediment classification; and in-situ geoacoustic, physical, optical, electrical, dynamic, and biogeochemical characterization of near surface sediments. US university participants (10 projects; 36 scientists, students and technicians) conducted temporal studies of acoustic bottom scattering; sediment classification; biological processes (bioturbation rates, and benthic community structure); radiochemistry (reworking depths, mixing and accumulation rates); biogeochemical processes controlling methane distribution; and sediment dynamics (near bottom currents and suspended loads). Sediment structure from the micron to the kilometer scales was investigated and sediment properties including physical, geoacoustic, geophysical and geotechnical properties were quantified by NRL and university scientists. German scientists (4 projects, 16 scientists from FWG, University of Kiel, and GEOMAR) concentrated on sediment classification; acoustic scattering; spatial and temporal distribution of the methane layer; in-situ measurement of sediment physical properties; and pore-water and bulk chemical characterization of sediments. Methane gas distribution, bubble size, and generation were investigated by scientists from both Germany and the US.

The following describes the experimental environment found at Eckernförde Bay between April-June 1993 and discusses a few of the potential scientific breakthroughs that are expected from these experiments. Eckernförde Bay sediments at the experimental site were soft, silty clays with evidence of considerable biological activity. Sediment organic contents (>5%) were very high. The uppermost sediments consisted of a 2-3 cm layer of brown oxidized mud which overlay a soft, black sediment with a distinct hydrogen-sulfide odor. Surface sediments contained numerous ovoid fecal pellets. Radiochemical profiles of excess ^{234}Th and bioturbation experiments with fluorescence tracer particles demonstrate that most biological mixing is restricted to the top 1-2 cm of the seabed. Sediment accumulation rates, determined by ^{210}Pb geochronology, were approximately 3-10 mm y^{-1}. These surface sediments were heavily-colonized by tube-dwelling, surface deposit-feeding spionid polychaetes (*Polydora ciliata*) and surface deposit-feeding bivalves (*Abra alba*). Other polychaetes, bivalves, and crustaceans were present in surficial sediments, some burrowing to 5-10 cm depth. Functional group classification, faunal abundances, organism size, and particle bioturbation experimental results are all consistent with the hypothesis that the benthic community is controlled by regular disturbance which maintains the community at a low level of complexity (i.e., a pioneering community). Ventilation of surface sediment with oxygenated bottom water by the small head-down, deposit-feeding *Capitella* sp. polycheates and tubificid sp. oligochaetes probably controls the depth of the brown oxidized layer and affects rates of near-surface biochemical processes. High sedimentation rates, near surface anoxic conditions, and restricted biological activity result in surficial sediments with very low values of shear strength (0.2-1.6 kPa), compressional (1430 m s^{-1}) and shear wave (4-7 m s^{-1}) velocity, and density (1.10-1.20 g cm^{-3}) and high porosity (85-91 %). Laminated bedding caused by alternating deposition of storm-suspended sediments (non-pelletal graded bedding) from adjacent shallow-water areas and a fair-weather supply of organic-rich suspended material (anisotropic pelletal fabric) is preserved in the sedimentary record. Sequence stratagraphic modeling of the complex interaction of biological, chemical and physical processes is underway.

CT-scans of pressurized core samples reveal only occasional methane gas bubbles from 20 to 100 cm depth while below a meter, numerous clusters of small methane bubbles are found . These bubbles occur in distinct horizons rather than in a continuous distribution. Gas bubble concentrations ranged from 0 to 2.0 % by volume within the main experimental site and as high as 5 % on the seafloor within a nearby pockmark. Larger gas bubbles were not spherical but had two long and one short axis (like a coin on edge). The acoustically turbid layer (i.e., the top of the gas bubble layer) migrates with season, occurring nearer the sediment-water interface during fall and winter months and deeper in the sediment during the spring and summer. It is postulated that fresh water percolation (pore fluid salinity) and seasonal changes in bottom water temperature affect the depth of the acoustic turbid zone by controlling rates of biochemical reactions and methane solubility. In-situ measurements of sediment geoacoustic properties show zones of highly attenuated compressional waves 50-150 cm below the sediment-water interface. The depth distribution of these zones corresponds to gas bubble distributions and probably result from scattering from methane bubbles. Shear waves appear unaffected by the presence of methane bubbles down to depths of two meters. Voids (probably gas bubbles) were evident in TEM micrographs of pressurized sediment samples collected from 2 meters below the sediment-water interface. High sediment permeability (10^{-4} - 10^{-6} cms^{-1}), for muds, is probably related to the very

loose microfabric (numerous channels and pores surrounding smaller clay particle aggregates) evident in TEM micrographs. Sediment fabric may also be used to explain the high values of sediment compressibility and apparent overconsolidation of near-surface Eckernförde mud. Sufficient data on both sediment structure (especially shear modulus and permeability) and methane bubble size and distribution are available to test models for the acoustic response of these gassy sediments. Data collected on the biogeochemical activity of methanogenic bacteria are more than sufficient to model the environmental processes responsible for the generation and distribution of methane gas bubbles. Study results also include stable isotopic characterization of methane and dissolved organic carbon and rates of microbial processes including sulfate reduction and anaerobic methane reduction, as a function of depth in the upper two meters of the sediment column. Therefore, predictive models relating biogeochemical processes, sediment structure and sediment behavior (acoustic, rheological and electrical) are obtainable using this extensive data set.

A unique set of time-series data on bottom currents, pressure, temperature, turbidity, and acoustic backscattering was collected during the experiments. Spectral analysis of bottom current and pressure data identified oscillations correlated with semi-diurnal tides and a Baltic-wide seiche. It is postulated that the relatively weak barotropic currents, driven by the Baltic-wide seiche, generate local near-resonant internal waves within Eckernförde Bay which, in turn, generate the stronger baroclinic currents that were observed. During the deployment, neither wind-generated waves or baroclinic currents generated bottom stresses sufficient to erode sediments; however, bottom stress was sufficient to advect sediment flocs eroded in shallower waters; thus clouding bottom waters with suspended material. This erosional event changed both bottom characteristics and benthic animal communities and also corresponded with changes in acoustic scattering. Analysis of high-frequency acoustic backscattering data demonstrated that scattering originates from a layer of free methane gas rather than the sediment-water interface. Spatial and temporal variability, including migrations, of free methane gas account for the spatial variability (meter scale) and temporal decorrelation (day scale) of backscatter images. The correspondence among bottom current speed, turbidity, pressure, and acoustic scattering is being investigated. Physical modeling of the effects of bottom boundary layer energetics on sediment characteristics and bottom communities is underway.

Normal-incidence, high-resolution, seismic reflection and side scan sonar profiling (over 1200 km) were conducted over a wide variety of sediment types (gassy and non-gassy muds, muddy sands, sands and glacial tills) in Eckernförde and Kiel Bays. Combined with sediment physical property data, the sonar data will be used to test and develop techniques for remote sediment classification.

Sediment properties in Eckernförde Bay were measured in sufficient detail to characterize sediment structure on scales of microns to meters. Collected data will be used to develop and/or test models of sediment behavior under a wide variety of natural and laboratory stress-strain conditions. Special consideration will be given the effects of gas bubbles on sediment mechanical and acoustic behavior. Sediment structure data will also be used to address fundamental acoustic issues, including the influence of sediment porosity and rigidity on propagation of acoustic energy and the effects of sediment volume inhomogeneity on high-frequency acoustic scattering.

The unique set of laboratory and in-situ measured geoacoustic data not only will provide for comparisons of techniques, but more importantly, when combined with the physical property data, can be used to test models of frequency-dependence in velocity and attenuation of compressional and shear waves in a poro-elastic medium.

An extensive study of "pockmarks" in Eckernförde Bay was conducted aboard the WFS Planet, on 26-27 October 1993. In-situ measurements of sediment physical properties, CT-scans of sediments retained at ambient pressure, sediment chemical characterization, and remote acoustic measurements show sediments with very high porosity (85%), low shear strength (1.14 kPa), and very high (> 5% by volume) but spatially variable gas contents. The high variability of near surface acoustic reverberation probably correlates with gas bubble distribution. Preliminary data analysis suggests that fresh water seeps together with methane gas embolism created local "pockmarks".

The final CBBLSRP experiment in Eckernförde Bay (27 June to 8 July 1994) included: a) continued intercomparison and development of sediment classification techniques; b) more extensive description of in-situ sediment structure, gas content, geoacoustic properties, and sediment behavior; c) verification of models to predict acoustic propagation and scattering in gassy sediments; d) geophysical investigations of Kiel Bay and using seismic subbottom reflection profiling and a bottom-towed geophysical sled (shear wave velocity and electrical resistivity); and e) continued studies of biological and biogeochemical processes, including the seasonal migration of methane bubble layers. A hyperbaric chamber was utilized to measure mechanical and acoustic properties from samples collected and retained at ambient pressures and to fix samples for TEM microfabric and biogeochemical studies. Results will be compared to similar measurements on sediments at atmospheric pressures. The size and distribution of methane bubbles were determined at ambient pressures on the aforementioned samples using CT-scan technology. These data are required to test models of acoustic volume scattering from methane bubble populations. Propagation, scattering, and absorption of near-incidence high-frequency acoustic energy, coincident with in-situ gradients of sediment geoacoustic properties (Acoustic Lance, Magic Carpet, ISSAMS, GISSAMS, Neptune, DIAS), were measured to test models of acoustic propagation in gassy sediments. Seasonal studies of fine-scale (vertical) rates of bioturbation, sediment accumulation rates, methane oxidation rates, sulfate concentration and reduction rates, and anaerobic methane oxidation rates were continued. Samples were successfully collected for accurate determination of in-situ methane concentrations and rates of production. These data should enable the development of a quantitative model which describes the biogeochemical processes controlling distribution and concentration of dissolved and free methane in Eckernförde Bay sediments.

1.2 DESCRIPTION OF THE WEST FLORIDA SAND SHEET EXPERIMENT

The experiment was conducted on the West Florida sand sheet 23 nm southeast of Panama City, Florida (9-30 August 1993). The shelf of the northeastern Gulf of Mexico is currently sediment-starved with most material deposited by the Appalachicola River during lower sea stands. Recent large scale seafloor morphology is controlled by hydrodynamic process, especially major storms.

Silt- and clay-sized particles are occasionally deposited over the sand sheet during severe storms. These finer sediments can be worked into the predominantly sandy surface sediments by biological activity creating a spatially and temporally variable sediment structure.

Acoustic surveys of a 20 km^2 area, using side-scan sonar, chirp sonar and 3.5 kHz echo sounding, allowed experimenters to delineate a 600 by 625 m primary experimental site which had uniformly high acoustic reflectivity. Preliminary observations of sediment collected with grabs, vibra cores and gravity cores combined with bottom video and diver observations suggest this high reflectivity could result of both fine-scale surface microroughness and from volume scattering from abundant shell material. Preliminary calculations suggest microroughness dominates backscattering at grazing angles greater than 10°; whereas, volume scattering is a significant component of backscattering for angles below 10°. Coarse-grained sandy sediments in this highly reflective area were mixed with shell hash, coralline algae fragments and numerous large mollusk shells. Sediments outside the experimental site were fine-grained sands of lower reflectivity, with little shell-hash and occasional muddy layers or inclusions. The highly reflective sediments had a significantly larger mean grain size (mean: 0.84 ϕ, range: 0.21-2.04) when compared to sediments with lower reflectivity (mean: 2.39 ϕ, range: 2.13-2.69 ϕ). Values of porosity were not significantly between the two sediment types (mean: 40.3 %, range: 36.7-46.4 %). Calculated sediments bulk densities ranged from 1.92 to 2.08 g cm^{-3} (mean: 2.01 g cm^{-3}). Microrelief in both types of sediments was dominated by biological features (mounds, pits and burrows) with little evidence of the type of wave-induced ripples or sand waves found in previous years).

Mean values of surficial sediment geoacoustic properties between sediment types were similar with in-situ near surface shear wave speeds of 80-150 m/s and compressional wave speeds of 1650-1740 m/s. Attenuation was high (100 - 700 dBm^{-1} at 400 kHz). Initial results show high variability in the values of compressional wave velocity and attenuation in the coarse sand (due to the heterogeneous mixture of shells and sand) but relatively low variability of those same properties in the fine sand. Spatial variability of sediment physical, geoacoustic and geotechnical properties will ultimately be determined from sediments collected using grab samplers (97 samples), gravity (14 samples) and vibra (8 samples) cores, and from 24 hand-collected diver cores. Surficial sediment properties provide ground truth to develop and test acoustic classification algorithms.

Acoustic boundary scattering experiments and time-lapse monitoring of environmental conditions were restricted to the highly reflective sediment. Preliminary results show high variability in acoustic scattering strengths over ping-to-ping, hour-to-hour, and day-to-day time scales. The near-bed hydrodynamic regime was dominated by reversing tidal currents with typical speeds of 10 cms^{-1} or less. Maximum bed shear stresses remained too low to resuspend or transport the sediments. The high temporal variability in acoustic scattering strengths must, therefore, be related to biologically induced changes in bottom roughness and bottom properties and/or to fluctuations in water column properties. CT-scans of sediment core samples show that the size distribution of shell material is distributed lognormally with a mean size of 0.18 mm. Laboratory analyses of sediment core samples and in-situ geoacoustic measurements will provide data on sediment structure from the cm to meter scales. Bottom microtopography will be

determined from approximately 65 stereo bottom photographs. Characterization of sediment structure (mm to meter scales) should enable us to predict frequency-dependent volume scattering. Measurements of bottom microroughness and sediment volume inhomogeneities from photographs and cores will be used to model the relative contribution of bottom interface roughness and volume scattering to high-frequency acoustic scattering and propagation. The contribution of spatial heterogeneity in sediment impedance-related properties, especially shells near the size of acoustic wavelengths, will be modeled and compared to experimental results.

1.3 PUBLICATION PLANS

Preliminary results of CBBLSRP experiments were presented at the AGU/ASLO "Ocean Sciences" meeting held in San Diego, CA (21-25 February 1994) and at the Acoustical Society of America meeting in Austin, TX (28 November- 2 December 1994). Proceedings of a workshop "Gassy Mud Workshop" held at FWG in Kiel, Germany (11-12 July 1994) were published by FWG (Wever, 1994). Twenty papers for a special issue of Geo-Marine Letters, devoted to CBBLSRP experiments are in review. Publication is planned for early 1996. A symposium devoted to modeling experimental results of the Eckernförde Bay experiments is scheduled for 26-30 June 1995 in Eckernförde, Germany. The results of that workshop will be the subject of a special issue of Continental Shelf Research.

1.4 ACKNOWLEDGMENTS

Operational support was provided by FWG, WTD-71, and University of Kiel. The CBBLSRP is supported by ONR, with contributing support from NRL and FWG. The Coastal Benthic Boundary Layer Special Research Program (CBBLSRP) research team consists of M.D. Richardson (chief scientist), D. Albert, A.L. Anderson, R.J Baerwald, R.H. Bennett, H.G. Brandes, K.B. Briggs, W.A. Bryant, W. Chiou, N.P. Chotiros, J.C. Cranford, A.M. Davis, R.W. Faas, K.M. Fischer, P. Fleischer, G.V. Frisk, R. Gammisch, K.E. Gilbert, R.R. Goodman, J.A. Hawkins, R.J. Holyer, D.R. Jackson, P.D. Jackson, J.J. Kolle, D.N. Lambert, Dawn Lavoie, Dennis Lavoie, G.R. Lopez, C.S. Martens, D.F. McCammon, E.C. Mozely, C.A. Nittrouer, T.H. Orsi, H.A. Pittenger, M.H. Sadd, S.G. Schock, A.J. Silva, N.C. Slowey, S. Stanic, T.K. Stanton, R.D. Stoll, D.J. Tang, G.E. Veyera, D.J. Walter, K.L. Williams, L.D. Wright, D.K. Young, R.K. Young, L. Zhang. Other contributors include I.H Stender, T. Wever, G. Fechner, and H. Fiedler of FWG, F. Abegg and F. Theilen of the University of Kiel, and M. Schlüter of GEOMAR.

1.5 REFERENCES

CBBLSRP Research Team. 1994. Forty-one abstracts from the AGU/ASLO "Ocean Sciences" Meeting held 21-25 February, 1994 in San Diego, CA. EOS, 75(3): pps. 159-160, 180-181, 201-203, 220-221.

CBBLSRP Research Team. 1994. Twenty-seven abstracts presented at the 128th meeting of the Acoustical Society of America held 28 November - 2 December in Austin, Texas. J. Acoust. Soc. Am., 96(5): pps. 3217- 3219, 3222-3224, 3245- 3247, 3263- 3266, 3286-3288.

Richardson, M.D. 1992. The Coastal Benthic Boundary Layer Special Research Program: Workshop Recommendations and Program Direction. Naval Research Laboratory Special Report SP 017:361:92

Richardson, M.D. 1993. The Coastal benthic Boundary Layer Special Research Program: A review of the First Year. Naval Research Laboratory Report NRL/MR/7431-94-7099.

Richardson, M.D. 1994. Investigating the Coastal Benthic Boundary Layer. EOS 75(17): 201-206.

Wever, T.F. 1994. Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, 11-12 July, 1994. FWG Report # 14.

2.0 PROJECT REPORTS FOR FY93

The following 23 reports summarize results for projects supported by the CBBLSRP:

2.1 Measurement and Description of Upper Seafloor Sub-Decimeter heterogeneity for Macrostructure Geoacoustic Modeling (Principal Investigators: A.L. Anderson, T.H. Orsi and A.P. Lyons)

CBBLSRP FY94 YEAR-END REPORT:

Aubrey L. Anderson, Thomas H. Orsi and Anthony P. Lyons
Department of Oceanography
Texas A&M University
College Station, Texas 77843-3146

INTRODUCTION

The primary goal of this project is to describe upper seafloor internal heterogeneity on a sub-decimeter scale (the decimeter being nominally the horizontal size of many seafloor core samples). This description is made with measurements of samples recovered from the seafloor. The samples are obtained with gravity corers, by diver coring and by subsampling box cores. The seafloor depth interval sampled ranges from the upper few 10s of cm up to 5 m, with most samples taken from the upper 1 to 2 m of the seafloor. For gassy seafloor regions, the samples are placed into pressure tight recovery chambers at the seafloor and recovered under *in situ* pressure. When it is deemed necessary, the gassy region samples are also maintained under refrigeration at near *in situ* temperatures until primary measurements are made. For this task, the primary method of measurement for all of the samples is x-ray CT scanning. Because the eventual goal is a contribution to geoacoustic modeling and an understanding of the interaction of acoustic waves and systems with the sampled seafloor, a variety of methods are used to calibrate the CT scan results so that the internal heterogeneity of material bulk density can be determined from the CT data. We physically subsample many of the cores and measure bulk density of these subsamples both to provide normal, high resolution physical sample density profiles and to serve as part of the calibration for interpretation of CT data as density. In some cases, with the generous cooperation of our CBBL colleagues Bill Bryant and Niall Slowey, we also have used measurements with their P-wave (and gamma density) logger for further comparison with the CT scan results.

In the annual report for FY93, we reported participation in two field trips to the CBBL site at Eckernförde Bay, Germany and one field trip to the CBBL measurement area off Panama City, Florida. During FY94 we participated in two more sampling expeditions to Eckernförde Bay and also worked on cores taken during a preliminary study of potential sites for CBBL carbonate region measurements in the vicinity of the Florida Keys. Core samples we have taken and/or worked with are listed in Table 1. This table includes both samples taken in 93 and those taken in 94 (this report year). The dashed horizontal line identifies the break point between Fiscal Years for the times that these cores were taken. All are listed for a variety of reasons. First, the complete list provides a good indication of the scope of material we are working with. Second, although many of these samples were taken during the last reporting period, only one set was well worked up during that time interval, as reported in last year's annual report. These previously reported samples are the box core subsamples from Eckernförde Bay - we had just been gained access to the CT data for the longer, gassy cores from this bay at the time of preparation of the annual report for FY93. Many more results are now available as will be described in the following. In addition to the core samples, we have had the opportunity to work with a collection of surficial shells from the Panama City site which were supplied to us by Kevin Briggs.

Table 1. Samples Used for Description of Internal Heterogeneity

IDENTIFIER	DATE	REMARKS
16-BS-TC	12 Feb 93	1m triple core, purposely not recovered under pressure, CT scanned @ Kiel
55-BS-GC	18 Feb 93	5m gravity core recovered in 1m sections in steel pressure chambers, CT scanned @ Kiel
227-BS-BC 250-BS-BC 260-BS-BC 263-BS-BC 264-BS-BC 268-BS-BC	May 93 " " " " "	Subsample cylindrical cores were taken from each of the listed box cores. These subsamples were transported to College Station (CS), Texas where they were CT scanned and physically subsampled for measurement of bulk density and other characteristics.
308-BS-DC	24 May 93	1.8 m core recovered for logging with expanding plugs in core liner to retain pressure. After logging, CT scanned @ Kiel
314-BS-DC	25 May 93	2m core, recovered in 1m sections in aluminum chambers, top section did not retain pressure, CT scanned @ Kiel & logged
315-BS-DC	25 May 93	2m core, 1m sections recovered in aluminum chambers under pressure, CT scanned @ Kiel
413-2-PC-DC 413-3-PC-DC 490-PC-DC	14 Aug 93 " 18 Aug 93	Diver cores of the upper ~17 to 24 cm of the sandy sediments, CT scanned in Houston, TX, logged& sampled(413-2,490) in College Station.
339-BS-DC	27 Oct 93	1m core recovered under pressure (RUP) in aluminum chamber, CT scanned @ Kiel
89-1-KW-DC 89-2-KW-DC	10 Feb 94 "	Marquesas site, ~ 22 cm diver cores, CT scans @ Houston, logged & sampled (1) in College Stn.
124-1-KW-DC 124-2-KW-DC	13 Feb 94 "	Dry Tortugas, ~27 cm diver cores, CT scans in Houston, logged & sampled (1) in College Stn.
706-BS-DC (P1)	29 Jun 94	2m core RUP, CT scanned @ Kiel
707-BS-DC (P2) 708-BS-DC (P3)	30 Jun 94 "	2m cores ~0.1 m apart & 2.5 m from 706, RUP, scanned @ Kiel
709-BS-DC (P4) 710-BS-DC (P5)	5 July 94 "	1m cores, ~ 0.1 m apart, floor of pockmark, RUP, scanned @ Kiel
711-BS-DC (P6)	6 July 94	3m core, 2m from 706, 4.5m from 707 & 708, RUP, scanned @ Kiel
712-BS-DC (P7)	6 July 94	1m core, near pockmark, RUP, scanned @ Kiel

The last seven cores listed in Table 1 were part of a set which was planned, collected, sampled and measured by a group of CBBL investigators who were interested in making several types of measurements either on the same samples of the seafloor or on companion samples collected near these and at the same time. In addition to the seven listed cores, another set of six companion cores were collected for gas analysis. Some of this gas analysis was carried out by Fritz Abegg in Germany and some by Chris Martens and Dan Albert. The designators of these 'gas cores' are 713-BS-DC through 719-BS-DC (Their temporary designators in the field were G1 through G6; the temporary field designators for 707 through 712 were P1 through P7 as indicated in Table 1). Most of the additional work on the 'P' cores was carried out in a recompression chamber on board the vessel PLANET. After CT scanning, these cores were returned to the ship for the following: compressional wave velocity logging by Mike Richardson and Kevin Briggs, obtaining samples for SEM/TEM measurements and mosaic construction by Dennis Lavoie, vane shear measurements both under pressure and after pressure release by Horst Brandes. Prior to the June/July field work at Eckernförde Bay, personnel of this heterogeneity project worked with all of the people listed here with both the P and G cores, plus Armand Silva, to prepare a plan for the sampling, scanning and field measurements of this collection of companion cores.

Other significant CBBL related activities which have been carried out by personnel of this project over the past year have included participating in organizing and co-chairing four Benthic Boundary Layer special sessions at the AGU/ASLO Oceans 94 meeting in San Diego, California, participating in several CBBL meetings to discuss results and plan future activities, and preparing and presenting papers as listed at the end of this report. Also, in addition to the direct measurements of heterogeneity, we have taken steps to relate this sediment internal volume information to the acoustic response of the seafloor and to the interaction of acoustic systems with the seafloor of the measured regions.

RESULTS

All of the cores listed in Table 1 (except the box core subsample 263-BS-BC) have been CT scanned. The long cores (diver or gravity cores) from Eckernförde Bay were scanned at a radiology clinic in Kiel, Germany on the same day they were collected (except 308-BS-DC, which was scanned one day after it was collected). The box core subsamples from Eckernförde Bay were transported to College Station and scanned with the x-ray CT scanner of the Engineering Imaging Center of Texas A&M University. A catastrophic failure of this scanner was the reason one of these subsamples was not scanned (though it was physically subsampled). This system failure also caused a change of the location of scanning for subsequent samples. The Panama City site and Florida Keys cores were all scanned at a petroleum company laboratory in Houston, Texas. The data for the scans made in Kiel are stored as compressed files. We transport the stored data on optical disks to College Station where the information is decompressed and stored as binary files. For all of the cores scanned during the four field sampling trips to Eckernförde (i.e., excluding the box core subsamples), we hold about 3 gigabytes of binary CT image data. Data for the remaining cores scanned at College Station and Houston total about 2 gigabytes. We work with these data in a variety of ways as discussed below.

Our annual report for last year presented examples of images of single CT scan 'slices' which were generated from data taken in Kiel by scanning pressure tight cores

taken from the floor of Eckernförde Bay. Such images of single slices and 'cut-away' three dimensional images which we construct from the full data base (of sequential individual CT scan 'slices') have allowed an unprecedented visualization of the interior structure of the undisturbed sediment core samples. We have used these to gain insight into the nature and origin of the internal heterogeneities within the upper seafloor. Many examples of such images have been presented in various forums over the past year. In addition to the value of such images for visualization of the sediment interior, the data base has many other valuable uses. Primarily this is true because of the ability to estimate fine-scale bulk density variations from the calibrated, stored CT data. The quantification of the heterogeneity has allowed new insights into the geoacoustic nature of the sediment volume and has permitted quantitative estimation of the acoustic response of the seafloor.

We will here initiate discussion of such quantification by discussion of the gassy samples for Eckernförde Bay. Examination and analysis of these samples progressed very rapidly, in part because we have been working for some time, and continue to work, on a companion ONR project specifically investigating the 'Acoustics of Bubbly Sediments.' Generating profiles of gas concentration versus depth is one of the first steps in quantifying the gas distribution information which is available in the CT scan data base. An example of such a profile is shown in Figure 1 for one of the cores from the Backscattering Tower location at the CBBL site in Eckernförde Bay. The upper 60 cm of this core contained no gas. The largest amount of gas and number of bubbles in this core occurred in the depth interval from 125 to 136 cm (beneath the seafloor). We have examined the gassy features in this depth interval in detail, including generating a list of all gas bubbles present in the interval and their size. This allows generating visual tools such as histograms of bubble size distribution over a depth interval for a core (the actual volume of the bubbles is determined from the data base, but for comparability of representation we typically plot such histograms in terms of the radii of spherical features of equivalent volume to those actually measured). Yet another step in quantifying the heterogeneity and relating it to acoustics is taken by our calculation of the volume backscatteing strength of gassy horizons. The results of one such calculation are shown in Figure 2. The heavy line in this figure represents the backscattering strength estimated for the bubbles occurring over the depth interval from 125 to 136 cm of the core illustrated in Figure 1. The light lines in Figure 2 are illustrations of the backscattering response of a few of the individual bubble sizes noted for this bubbly interval. These results are for one method of making such calculations and one of the goals of the CBBL project is to examine such predictions from several calculation methods. We have also generated a gas concentration depth profile for a sample from the gassy floor of a pockmark in this same region and found that the gas concentration is in general higher than that at the site of core 315 and that the gas occurs with a more nearly continuous distribution with depth. We are in the process of examining a different method for estimating the acoustic response of the bubbly seafloor. We now identify each gassy feature and determine its volume (as before) but now we also note the location of the depth of the center of gravity of each feature in the sediment column. This provides the information required to estimate the impulse response of a segment of the seafloor with the contribution of each gas bubble appropriately related (in space or time) to other features (and the beginning of the seafloor) Such information is allowing more complete simulation of the interaction of an acoustic system with the bubbly seafloor.

The images, quantification of the heterogeneity and acoustic modeling we have carried out with the data from the CBBL samples allow several observations about the

sampled gassy seafloor. [1] The gas bubbles within the seafloor are not distributed continuously with depth. The bubbles begin almost immediately below the water sediment interface in the floor of the pockmark but do not begin until several 10's of cm into the seafloor at sites outside the pockmark (specifically at the backscattering tower site). The gas concentration varies considerably with depth in the pockmark floor, but there is some non-zero amount of gas over the entire 70 cm sampled depth interval. The highest gas concentration noted occurred in the pockmark floor and was about 4.5 % by volume. By contrast, the sites sampled outside the pockmark had maximum gas concentrations of about 2 % with most concentrations being considerably less than this. The gas typically occurred only over 'horizons' of a few cm thickness with very low or zero concentrations between these horizons (and there was no gas from the sediment surface down to a depth of several 10's of cm). The gas bubbles occurred with several shapes ranging from almost spherical to highly non-spherical. Many of the gassy features had the appearance of gas filled fractures with one of the long dimensions of the fracture in the vertical orientation (in the original seafloor orientation of the sample). Smaller bubbles are more nearly spherical with increasing deviation from the spherical shape typically coinciding with increasing gas bubble volume. Initial estimates of acoustic backscattering cross section, made with many assumptions, indicate that the bubbles observed should produce volume backscattered signals which are orders of magnitude greater than the volume backscattering resulting from other observed internal heterogeneities in these samples (with the possible exception of dense concentrations of shells). For the frequency range of these calculations (up to about 40 kHz), the deviation from sphericity of some of the bubbles probably is not a factor in the acoustic internal volume scattering. However, for higher frequencies, the bubble shape is likely to be a factor and may cause a variation of volume backscattering strength with azimuth angle relative to a 'patch' of gassy seafloor.

An example of a different type of sediment heterogeneity is provided by the samples from the Panama City site. Figure 3 provides information for one of the cores from this site. The data presented combine information from both our CT scanning results and measurements with the gamma ray density and p-wave logger. Working with the data base from the CT scans, we have determined that the number frequency of occurrence of sizes of the shells making up the upper layer of this seafloor are lognormally distributed as shown in Figure 4. It was anticipated that the primary origin of backscattered energy for this seafloor would be the roughness of the water-sediment interface. We tested this assumption by independently calculating the backscattering strength for the interface roughness and that for the volume scattered energy from a distribution of shell pieces as indicated in Figure 4. These calculations were made for 40 kHz energy and with a wide range of grazing angles for the interaction with the seafloor. Over most of the angular interval, the backscattering was indeed dominated by interface roughness with only a two or three decibel increment added by the volume scattering to produce a total scattering strength. However, for low grazing angles of the ensonifying field, scattering due to the interface roughness decreases dramatically with decreasing angle, much more rapidly than any predicted angular change of the volume scattering. The net result of this predicted behaviour is that volume scattering is a significant component of the overall backscattering strength for angles below about 10 degrees. For lower angles, omitting the volume scattering component could result in a backscattering estimate which is too low by an order of magnitude. These preliminary results suggest that both volume and interface scattering may be important components of the overall scattering interaction with this seafloor, at least for some range of grazing angles.

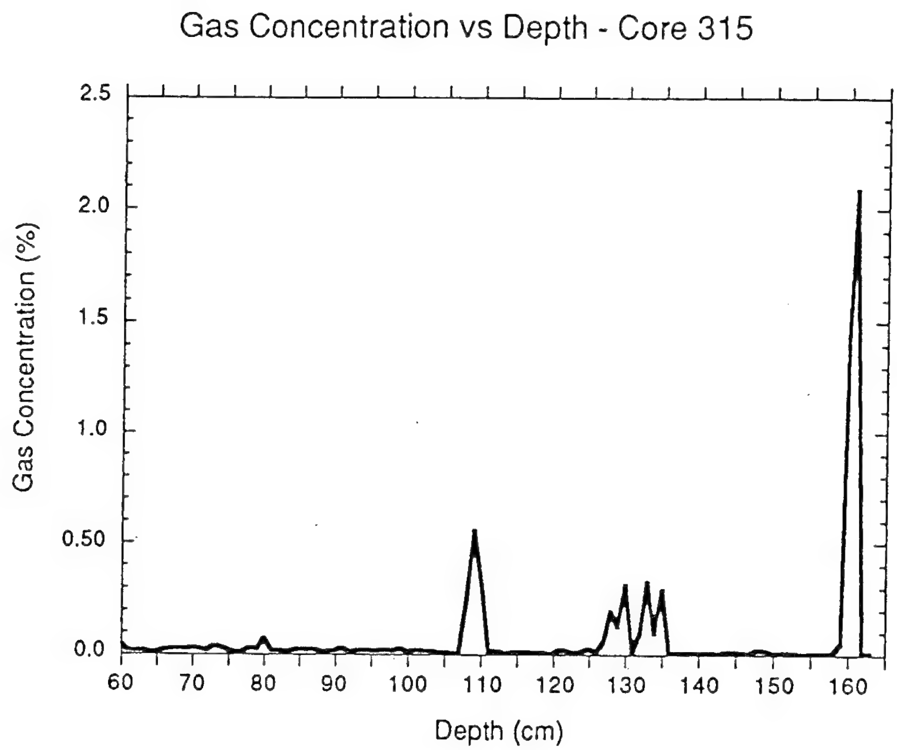


Figure 1. Depth Profile of Free Gas Volume Concentration Based on 3-D CT Scan Data Base for Backscattering Tower Site Core.

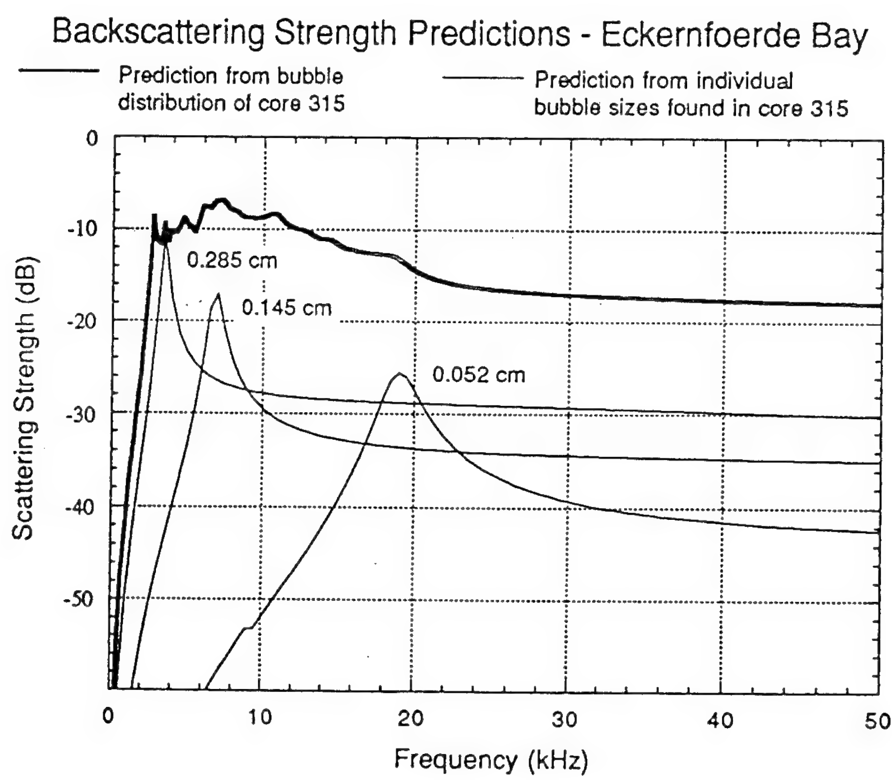


Figure 2. Normal Incidence Backscattering Strength Estimates from CT Data.

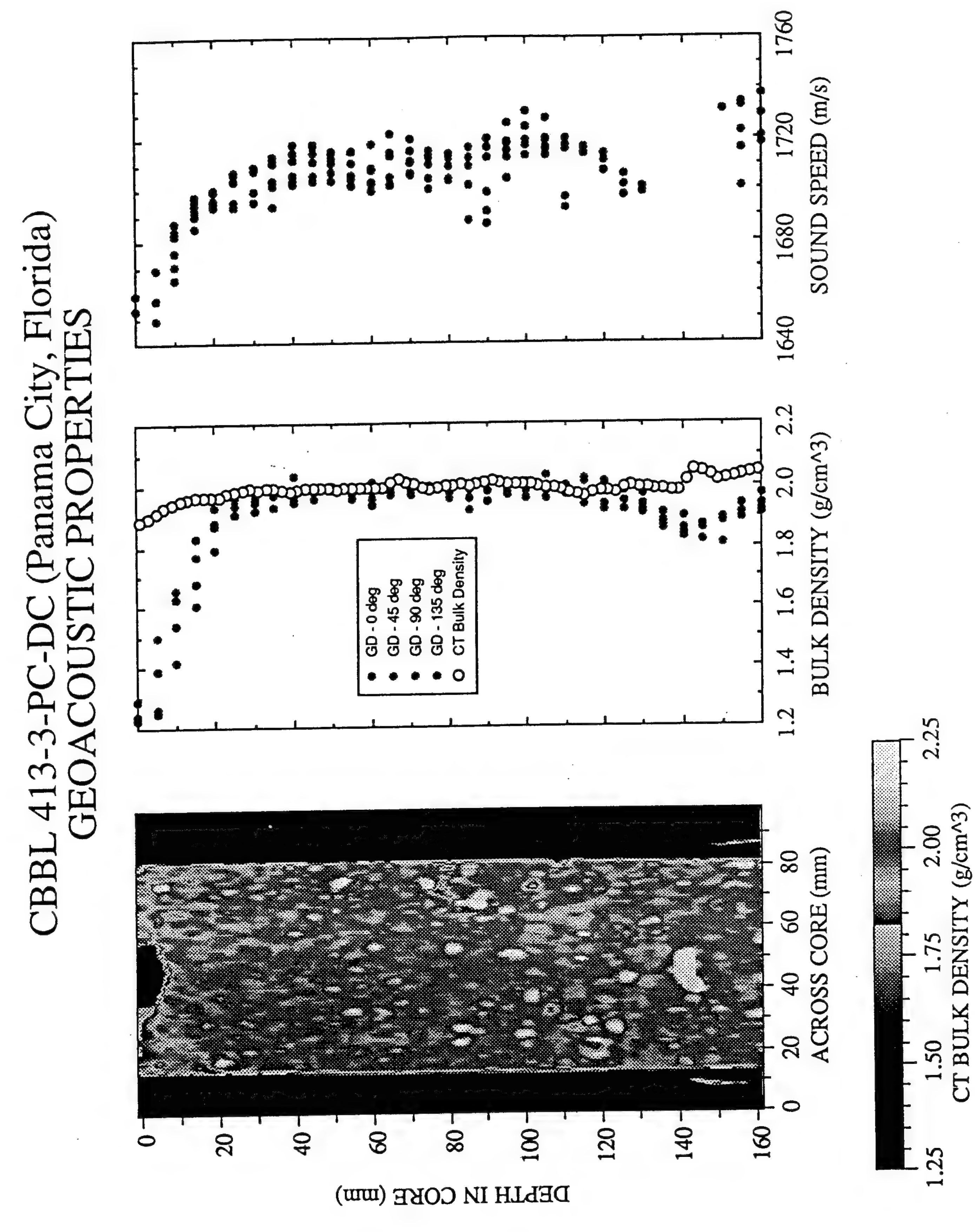


Figure 3. CT Scan and Logger Data for Panama City Diver Core.

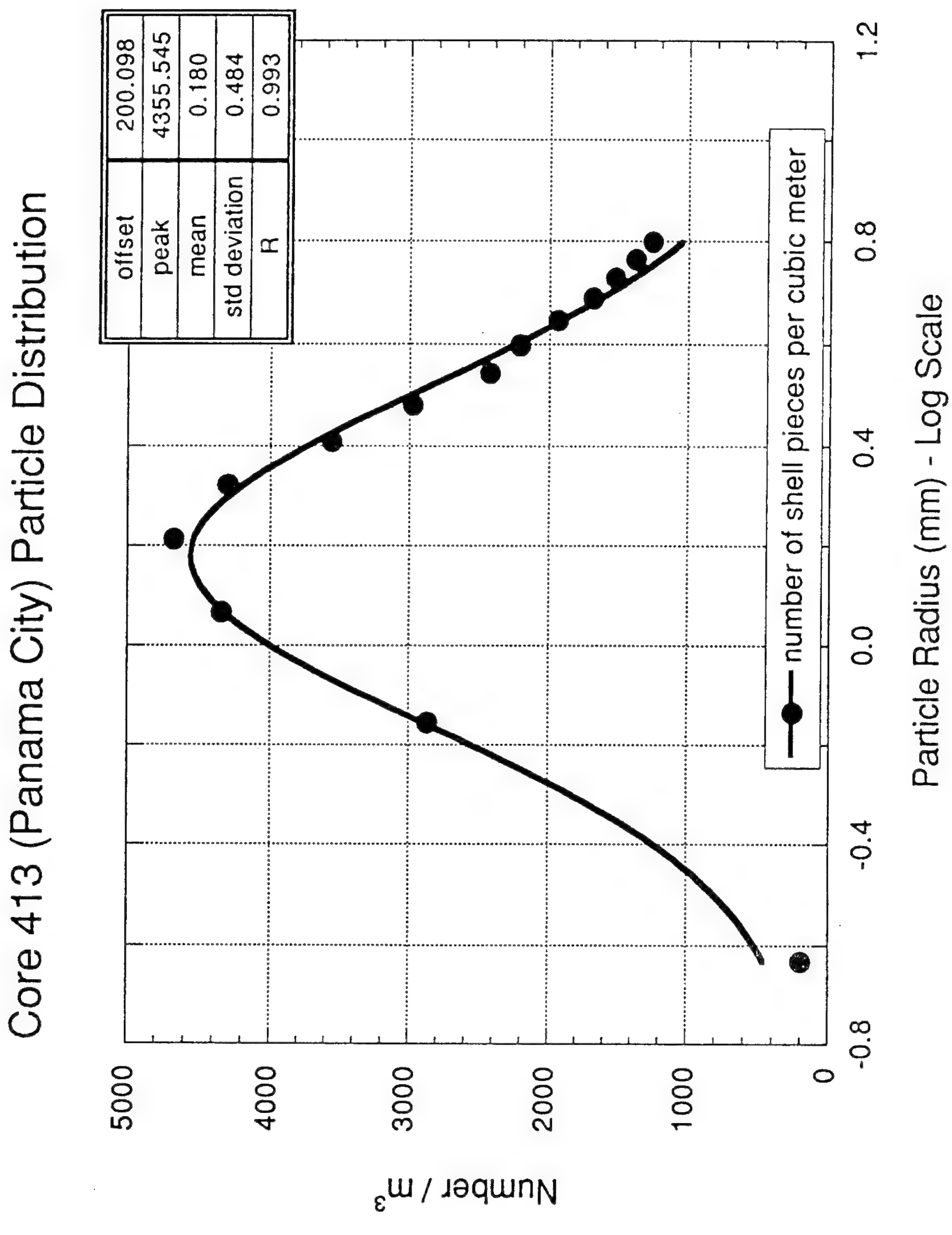


Figure 4. Distribution of Particle Sizes from CT Data.

PUBLICATIONS AND PRESENTATIONS (First two years)

T.H. Orsi, A.L. Anderson and A.P. Lyons 'X-ray tomographic analysis of sediment macrosctructure and physical property variability in Eckernförde Bay, Western Baltic Sea' submitted for publication in special issue of Geo-Marine Letters based on CBBLSRP papers presented at OCEANS 94.

A.P. Lyons, M.E. Duncan, J.A. Hawkins and A.L. Anderson 'Predictions of the acoustic response of free methane bubbles in muddy sediments' accepted as an invited paper for the special session on High Frequency Inversions for Sediment Properties at the 128th meeting of the Acoustical Society of America in Austin, Texas, November 28, 1994.

M.D. Richardson, S.R. Griffin, K.B. Briggs, A.L. Anderson and A.P. Lyons 'The effects of free methane bubbles on the propagation and scattering of compressional and shear wave energy in muddy sediments' accepted for presentation in the special session on High Frequency Inversions for Sediment Properties at the 128th meeting of the Acoustical Society of America in Austin, Texas, November 28, 1994.

T.H. Orsi and A.L. Anderson 'Bubble characteristics in gassy sediments' Gulf Coast Association of Geological Societies Convention, Austin, Texas, October 5-7, 1994.

F. Abegg and A.L. Anderson 'The acoustic turbid layer in soft mud: methane concentration, saturation and bubble characteristics. Examples from Eckernfoerde Bay, Germany' Third International Conference on Gas in Marine Sediments, Texel, The Netherlands, September 25-28, 1994.

T.H. Orsi, A.L. Anderson and A.P. Lyons 'Geoacoustic characterization of shallow-water marine sediments for high frequency applications' IEEE-OES OCEANS 94, Brest, France, September 13-16, 1994.

A.P. Lyons, A.L. Anderson and T.H. Orsi 'Modeling acoustic volume backscatter from two shallow-water marine environments by side-scan sonar' IEEE-OES OCEANS 94, Brest, France, September 13-16, 1994.

T.H. Orsi 'Computed tomography of macrostructure and physical property variability of seafloor sediments' unpublished PhD thesis, College Station, TX, Texas A&M University, August 1994.

F. Abegg, A.L. Anderson, L. Buzi, A.P. Lyons and T.H. Orsi 'Free methane concentration and bubble characteristics in Eckernfoerde Bay, Germany' Gassy Mud Workshop, Forschungsanstalt der Bundeswehr für Wassershall und Geophysic (FWG), Kiel, Germany, July 11-12, 1994.

A.L. Anderson, A.P. Lyons, L. Buzi, F. Abegg and T.H. Orsi 'Modeling acoustic interaction with a gassy seafloor including examples from Eckernfoerde Bay' Gassy Mud Workshop, Forschungsanstalt der Bundeswehr für Wassershall und Geophysic (FWG), Kiel, Germany, July 11-12, 1994.

A.L. Anderson and F. Abegg 'Measurement of gas bubble concentration and distribution in the seafloor of Eckernförde Bay, Germany' 1994 AGU/ASLO Ocean Sciences Meeting, San Diego, California, February 21-25, 1994.

A.P. Lyons, A.L. Anderson and T.H. Orsi 'Estimates of volume scattering cross section and related parameters due to property variability in Eckernförde Bay' 1994 AGU/ASLO Ocean Sciences Meeting, San Diego, California, February 21-25, 1994.

T. H. Orsi and A.L. Anderson 'Macroscale heterogeneity of sediments from Eckernförde Bay (Western Baltic Sea): Quantitative characterization using x-ray CT' 1994 AGU/ASLO Ocean Sciences Meeting, San Diego, California, February 21-25, 1994.

K. M. Fischer and T.H. Orsi 'Porosity gradients in Eckernfoerde Bay (Baltic Sea), Germany: carbon content' 1994 AGU/ASLO Ocean Sciences Meeting, San Diego, California, February 21-25, 1994.

T.H. Orsi 'Computed tomography of macrostructure and physical property heterogeneity in surface sediments of Eckernförde Bay (Western Baltic Sea)' 6th Annual Student Symposium, College of Geosciences and Maritime Studies/Ocean Drilling Program, Texas A&M University, College Station, TX, February 19, 1994.

A.P. Lyons and T.H. Orsi 'Characterization of seafloor property variability and estimates of acoustic volume scattering cross section in Eckernförde Bay, Germany' 6th Annual Student Symposium, College of Geosciences and Maritime Studies/Ocean Drilling Program, Texas A&M University, College Station, TX, February 19, 1994.

T.H. Orsi 'A method for quantifying bubble characteristics in gassy aqeous sediments' 6th Annual Student Symposium, College of Geosciences and Maritime Studies/Ocean Drilling Program, Texas A&M University, College Station, TX, February 19, 1994.

T.H. Orsi and A.L. Anderson 'Computer tomography of biological structures in marine sediments' IEEE-OES OCEANS 93, Victoria, Canada, September, 1993.

2.2 Sediment Properties from Grain and Microfabric Measurement (Principal Investigators: R.H. Bennett, D.M. Lavoie, R.J. Baerwald and M.H. Hulbert)

SEDIMENT PROPERTIES FROM GRAIN AND MICROFABRIC MEASUREMENT

Richard H. Bennett, Dennis M. Lavoie (NRL), Roy J. Baerwald (University of New Orleans), and Matthew H. Hulbert (Resource Dynamics, Inc.)

LONG-TERM SCIENTIFIC OBJECTIVES

• To model the dynamic response of sediment bulk physical properties to environmental processes, applied stresses, and phenomena such as high frequency acoustic energy, based on fundamental micro-scale structure and properties.

Background: The seabed's interaction with such phenomena as high frequency acoustics is controlled by the physical properties of the sediment. Under given effective stress conditions, the important physical properties are: porosity, pore geometry, pore connectivity, permeability, electrical resistivity, bulk modulus, and shear modulus. These properties are determined by the fundamental properties of the sediment constituents, such as grain size, mineralogy, physico-chemistry, fabric, organic matter, and free gass content. The multi-phase sediment is described as a three-dimensional microstructure system consisting of various solid phase materials — primarily mineral particles and condensed organics — distributed within a water (and sometimes gas)-filled pore network. The organic solids are in the form of adsorbed layers on the minerals or as polymeric gels between the minerals. The solid phases

associate according to physico-chemical relationships governed by the attractive and repulsive forces between them and the chemical nature of the pore fluid. Free, undissolved bubbles of gas are occasionally present in surficial layers of sediment; when present, gas may be important in altering sediment properties. Our premise is that, if we can determine the nature of the solid constituents and their spatial relationships (microfabric), we can begin to estimate the physico-chemical forces involved in the association and ultimately model the sediment bulk properties. Once these parameters and relationships of the phases are understood, we can begin to model sediment's dynamic response to environmental processes and stresses. The hypothesis is that fundamental, micro-scale properties of sediment structure control the expression of macro-scale, bulk properties.

PROJECT OBJECTIVES

• To develop relevant parameters of sediment microstructure (microfabric and physico-chemistry, organic content, mineralogy, grain size, grain shape, and grain size distribution).

• To develop a sediment model using these parameters to predict crucial sediment bulk physical properties (porosity, pore geometry, pore connectivity, permeability, electrical resistivity, bulk modulus, shear strength, and shear modulus).

•To extend the model to static and dynamic cases of applied stress and other energy input.

Approach: The general approach is to integrate proven methodologies for studying sediment microstructure and physical properties to develop

parameters suitable for inclusion in formulations modelling microfabric and macroscale sediment behavior.

The specific methodologies that will be used in this approach are as follows:

1) Microfabric analysis, including grain/pore parameters, and parameterization of two-dimensional TEM micrograph using image analysis techniques. Eventually, the image analysis will be extended to three-dimensions by 3-D volume reconstruction and visualization techniques in order to develop a physical model at the micro-scale. Confocal scanning laser microscopy (CSLM) in combination with fluorescent stains also will be tested for its utility in non-destructive imaging of sediment structure and pore pathways.

2) Organic and biologicals. Specific and general stains for fluorescence and electron microscopy will be used to determine spatial relationships to the microfabric and morphology of organic biopolymers and their microbiological sources in the natural sediments.

3) Mineralogy. Selected area diffraction (SAD) will be used in the TEM to determine mineralogy on the microscopic scale in relation to the microfabric and organics.

4) Physical properties: Measurements by other CBBL participants will be used in our analyses and include physical properties determined on the same samples examined for microstructure. These measurements will include: grain size, porosity, permeability, bulk modulus, shear modulus, and electrical resistivity.

5) Modeling. The work will first be directed at developing physico-chemical models of the sediment microfabric based on parameters developed by the microfabric analysis. Presently, there are no models that handle the dense, heterogeneous media represented by fine-grained marine sediments, so the results from this work are expected to be highly significant. The resulting models will then be used as a basis for the modeling of sediment bulk properties.

PROGRESS AND CURRENT STATUS

A) New results from analysis of the FY93 samples include:

- Imaging of biogenic polymers and microorganisms in the Eckernförde sediments using rapid processing techniques **(Fig 1)**. These techniques tend to disrupt the clay microfabric, so, based on the results, we modified our processing scheme for the FY94 field experiment. We have been able to image the biological and biogenic organic components in their true spatial relationship with clay microfabric .
- Demonstration that at least one aspect of Eckernförde Bay microfabric — porosity — can be determined by image analysis techniques to a reasonable degree compared to bulk measurement techniques **(Fig. 2).**
- Use of microfabric analysis to explain unusual physical and mechanical properties, specifically: unusually low shear modulus; behavior of shear modulus upon remolding; apparent two-phase behavior of the effective stress-permeability curve **(Fig 3)**; high permeability for such a high clay content; and rapid dissipation of induced excess pressure. The apparent reason is the existence of large and numerous channels and pores surrounding somewhat smaller aggregates of clay particles. Permeability

probably occurs primarily within these channels rather than within the relatively low porosity-aggregates, resulting in sediment behavior that is more characteristic of coarser-grained sediments. These channels apparently collapse readily under small effective stress, changing the grain-to-grain contacts, permeability, and shear strength. The facts that porosity is relatively low within clay particle aggregates and that most of the biogenic particles are found outside of the aggregates imply that the channel and aggregate structure of this sediment will control the diagenesis, with possible implications for the microfabric model being developed.

- Description of permeability and excess pore pressure fields for a small cross-section of Eckernförde Bay **(Fig 4).** These indicate that there is considerable spatial variablity within the sediment.

B) The FY94 return field trip to Eckernförde Bay was completed sucessfully. The emphasis this time was parallel sampling in conjunction with Dawn Lavoie, Kevin Briggs, David Young, Armand Silva, Horst Brandes, and Aubry Anderson to better relate microfabric to index properties, sedimentology, x-radiography, and CAT features. As much as possible, subsamples for the various analyses were taken at the same level on the same cores to minimize spatial variability. Many of these parallel samples were collected in the hyperbaric chamber. Analysis is still under way.

C) Tests on time-gated laser imaging of microfabric using the facilities of Dr. Rentjes, NRL-DC, were not encouraging and we are no longer pursuing this avenue.

D) A preliminary test on wet Eckernförde mud using a newly acquired confocal scanning laser microscope (CLSM) and volume visualization software indicated a penetration depth of about 50 μm was possible. We will conduct

further tests on penetration vs. resolution to determine the feasibility of using this technology to non-destructively image pore space in 3-D in clay sediments. Regardless of the outcome, it appears that the visualization software will be applicable to our original approach of high-resolution 3-D visualization using TEM-generated image planes, negating the need for use of the supercomputer. The CLSM is being made available by Dr. Brenda Little, MIC Section.

E) The search continues for better modelling techniques to meet our goals as the acquisistion of field data progresses. We have researched and discarded fractal techniques as a viable approach, and are now pursuing concepts involving quantification of contact geometry suggested by Bennett.

1994 PRODUCTS

Two papers — one focused on the pore pressure field and one on the relation between microfabric and index properties — describing the results of the FY93 field experiment in Eckernförde Bay were presented at the Gassy Mud Workshop held at FWG in Kiel. These papers were then expanded for submission to the Special Volume of Geo-Marine Letters being prepared for the CBBL/SRP.

LEGENDS:

FIGURE 1: Example of microorganism and associated biopolymer observed in Eckernförde Bay. The net-like structure is similar to that seen in other environments, such as bayou sediments (Baerwald, unpublished data) and lacustrine suspensoids (G.C. Lepard, A. Massalski, and D.R.S. Lean, 1977, Protoplasma 92:289-309)

FIGURE 2: Porosity determined by standard bulk measurements (a) and by image analysis of void space in 2-D sections (b). Porosity of just the clay particle aggregates was ~35 % compared to ~75 % when channels and pore space were included in the analysis. Hardware limitations (inability to acquire low magnification images) probably resulted in underestimates of image porosity (from Lavoie, Lavoie, Pittenger, and Bennett submitted to GeoMarine Letters).

FIGURE 3: Permeability vs. effective stress. Note the high permeability overall and the rapid decrease in permeability with low application of effective stress in what appears to be a two-phase manner controlled by the channel-and -aggregate structure of the sediment. (from Lavoie, Lavoie, Pittenger, and Bennett submitted to GeoMarine Letters)

FIGURE 4: (a) Permeability field in Eckernförde Bay, May 1993. Measurements were taken approximately 1.8 m apart and indicate considerable spatial variability. (b) Excess pore pressure along the same sample line. Note again the spatial variability as well as the generally low values, including the shaded areas where excess pore pressure is approximately zero or slightly greater than effective stress, impling unstable conditions. (from Bennett, Anderson, Meyer, and Lavoie, submitted to GeoMarine Letters)

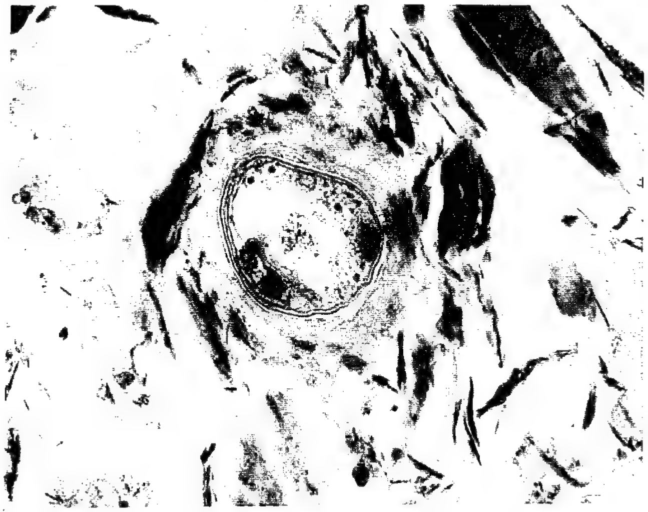


FIGURE 1

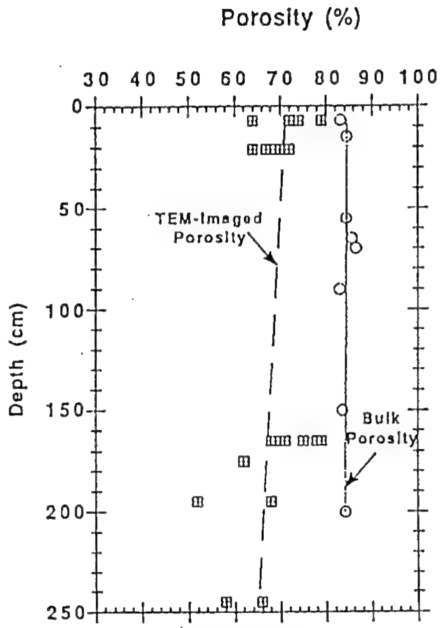


FIGURE 2

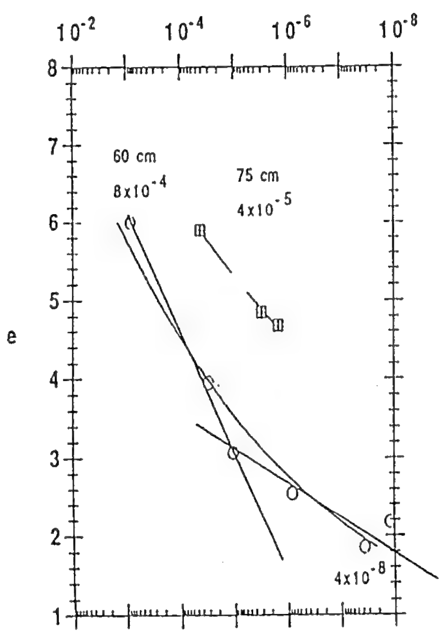


FIGURE 3

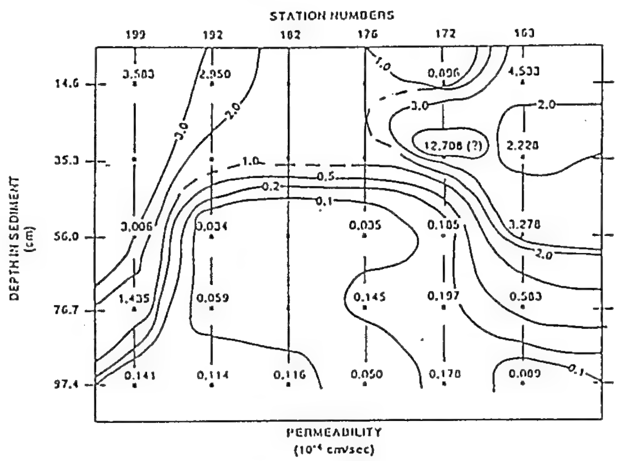


FIGURE 4a

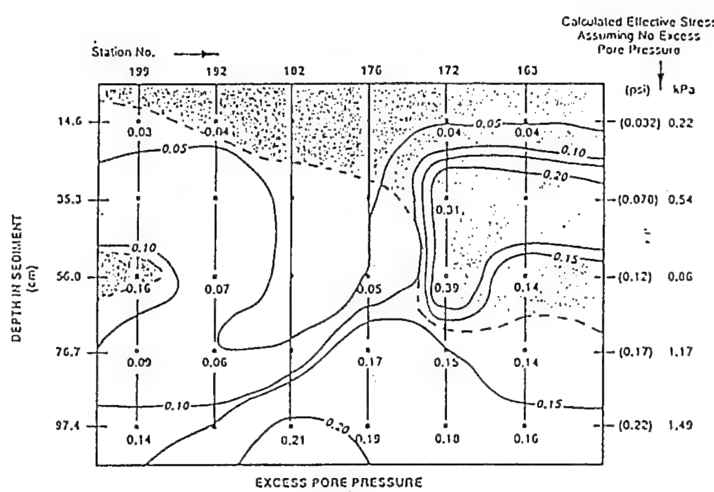


FIGURE 4b

2.3 High-Frequency Acoustic Scattering from Sediment Surface Roughness and Sediment Volume Inhomogeneities (Principal Investigators: K.B. Briggs and M.D. Richardson)

High-Frequency Acoustic Scattering from Sediment Surface Roughness and Sediment Volume Inhomogeneities

Kevin Briggs and Michael Richardson, NRL Code 7431, Stennis Space Center, MS 39529-5004

Objectives

Investigators attempted to characterize inhomogeneities within the sediment volume in order to better understand geoacoustic variability at the Eckernförde experiment site as well as the pockmark site. Also, a pre-site survey was conducted in the Key West area for experiments beginning in 1995. Laboratory analyses (grain size distribution and grain density) of sediments from the FY93 experiments were started. Sediment properties that were measured from all sites in order to correspond to acoustic scattering model inputs were sediment compressional wave velocity and attenuation (at 400 kHz), sediment porosity and sediment density. In addition, sediment density to x-rays, electrical resistivity and sediment shear strength were measured at the Eckernförde sites and x-radiographs were collected from the Key West survey. Smith-McIntyre grabs were collected to ascertain the type and variability of sediment types within the Key West area.

Of particular importance to this effort was the lateral variability of sediment velocity and porosity within the pockmark and along a transect over which sediment classification sonars had collected data. These measures were obtained through standard "ear-muff" transducers through core liners for the velocity and water content assays. X-radiography and an electrical resistivity core scanner developed by Peter Jackson for measurement on x-radiograph cores were used in the Eckernförde experiment site.

Accomplishments

Eckernförde Pockmark

Ten 6.1-cm-diameter cores were collected from the PLANET in Oct-Nov 1993 for the purpose of measuring sediment compressional wave velocity and attenuation within and near the pockmark. Porosity was measured on six of the ten cores. Four of the cores were collected by divers using pressure plugs to preserve intact any methane present in the sediment; the six remaining cores were collected as subcores from a box corer. Velocity and attenuation measurements were made on pre- and post-pressure-released cores. Significant amounts of gas were present in only two cores (340 and 341). Sediment sound velocities were concentrated in the range of 1440 to 1520 m s^{-1} (Fig. 1) with some values as low as 713 m s^{-1} occurring at 20 cm where free gas was present; attenuation varied from 22 to 156 dB/m with some values as high as 959 dB m^{-1} where free gas was present (Fig. 2); porosities varied from 93% at the surface to 69% in fine sand laminae occurring at 10-20 cm (Fig. 3).

Twenty-three diver vane shear tests were made to determine in-situ shear strength within and near the pockmark. Sixteen vane shear tests were performed from box cores; the remaining seven were performed by divers in situ. Frictional components were accounted for by tests performed without the vane. Corrected shear strength values varied from 0.2 to 3.0 kPa (Fig. 4).

Eckernförde FY93 Experiment Site

Diver cores and subcores from box cores were collected at the site of the FY93 experiment while aboard the PLANET during June-July 1994. Sixteen x-radiograph cores were collected and x-rayed and five were measured with the electrical resistivity core scanner. Five box cores were collected along the "Schock line" from Stollergrund to Mittelgrund for ground truthing. From these five box cores, five subcores for geoacoustic property analyses and six x-radiograph subcores for sediment structure analysis were collected.

Sediment sound velocity for the five cores along the "Schock line" varied with sediment type. Sediments varied from fine sand to muddy sand to sandy mud to mud (right to left in Fig. 5). Fine sand exhibited values of sound velocity of approximately 1640 m s^{-1} and muds varied from 1620 to 1463 m s^{-1}. Compressional wave attenuation exhibited patterns attributable to banding or layering of sand and mud (Fig. 6). Sediment porosity in the fine sand ranged from 40.8 to 44.4% (Fig. 7).

Electrical resistivity patterns within the x-radiograph cores reflected the strong variability characteristic of storm-generated laminae and inclusions (Fig. 8). The laminae were denser, coarser-grained sediments and the occlusions were mostly shells and infilled burrows.

Key West

Six diver cores were collected from the R/V COLUMBUS ISELIN in February 1994 for the purpose of measuring sediment compressional wave velocity and attenuation, grain size and porosity. Four cores were located in the area north of the Marquesas Keys and two were located south of Garden Key in the Dry Tortugas. Two x-radiographic cores were collected in the Marquesas Keys area. In addition, 38 gravity cores were collected on which compressional wave velocity and attenuation were measured with ear muff transducers. Sediment porosity was determined from two gravity cores, one from each of the two sites. A video camera drift was performed over the center of the Marquesas Keys site.

Sediments in both areas were carbonate *Halimeda* muddy sands and sandy muds with significant amounts of mollusk shell hash. Penetration of the diver cores into Marquesas Keys sediments was restricted to a maximum of 22 cm, with the majority of cores reaching only 12 to 14 cm depth in the sediment. A coarse shell layer which hindered further penetration in the flocculent mud was located at a depth of 5-10 cm. The shells extended to an unknown depth in the sediment and were so numerous as to appear to constitute a "grain"-supported sediment. The sediment-water interface was relatively smooth and ripple-free with occasional biogenic mounds but numerous holes resembling openings to *Callianassa* burrows. Diver cores penetrated sediments in the Dry Tortugas site down to 30-32 cm. Shells were present at greater depths in the sediment than at the Marquesas Keys site.

Sediment sound velocities in diver cores varied from 1511 to 1572 m s^{-1} at the two sites (Fig. 9). Attenuation of the 400-kHz signal was very high in the upper 5-10 cm of sediment due to the presence of shell hash. Variability in values of compressional wave attenuation was higher in the Marquesas Keys site than in the Dry Tortugas site, especially below 5 cm sediment depth (Fig. 10). This resulted from the inclusion of many shells and shell fragments in the carbonate matrix.

Sediment porosity varied from 51 to 71% at the two sites (Fig. 11). There are steep

gradients in porosity with depth in the top 10 cm of sediment. Wet bulk density values varied from 1.52 to 1.91 g cm^{-3}, and averaged 1.75 g cm^{-3} at the two sites. An average grain density for the carbonate sediment of 2.76 g cm^{-3} was determined from dried sample determinations.

Data from the gravity cores were consistent with diver cores collected from the same sites. Sediment porosity decreased to 51% at 30 cm sediment depth and varied little below that depth at either site (Fig. 12). In the Marquesas Keys site, sediment sound velocity decreased to a mean of approximately 1530 m s^{-1} at 1 m and stabilized below that depth in the sediment. In the Dry Tortugas site, by contrast, sediment sound velocity averaged approximately 1580 m s^{-1} down to 130 cm sediment depth. Variability in sediment sound velocity was greater at the Marquesas Keys site (Figs. 13 and 14). Compressional wave attenuation in the sediments of the two sites is high (mean near 425 dB m^{-1}) and is highly variable as indicated by a range of 100 to 720 dB m^{-1} (Figs. 15 and 16).

Preliminary Conclusions

Eckernförde

Vertical variability of sediment compressional wave velocity and attenuation and porosity in the sediments of Eckernförde, though generally low, encompasses values measured both within the pockmark and in the center of the bay.

The sediments in the pockmark have somewhat higher porosity, lower sound velocity and lower shear strength, especially near the sediment-water interface, probably related to the process of gas ebullition.

The dissolved methane saturation horizon in the pockmark is about 15 cm sediment depth. This horizon occurs at a shallower depth than outside the pockmark.

There is surprising variability in the location of free gas within the pockmark, as evidenced by the collection of samples containing no gas in the top 35 cm of sediment and samples containing gas near the sediment surface.

Vane shear strength values generally increased with depth and showed some variability at depth in the sediment corresponding to the depth where free gas presumably exists.

Electrical resistivity measurements of x-ray cores show high lateral and vertical variability. Measurements made on cores with holes pre-drilled in one side give better quality data due to reduced disturbance from the measurement process.

Key West

The Marquesas Keys experiment area exhibits high variability in sediment sound velocity and attenuation due to the presence of mollusk shell fragments deeper than 5-10 cm in the sediment. The values for sound velocity and attenuation in the Dry Tortugas site are less variable, though the presence of shell hash has been observed. Porosity exhibits a strong gradient with increasing depth in the sediment, but only in the top 10 cm.

Observations of the sea floor reveal the Marquesas experiment site to be a soft, flocculent sediment with numerous burrows, possibly deep-burrowing crustaceans, and a site with influences from anthropogenic disturbances from shrimp trawling. The Dry Tortugas experiment site appears to be biologically active, but characterized by different fauna possibly resulting from a lack of trawling within the marine sanctuary.

Presentations and Publications

Briggs, K.B., M.D. Richardson and D.B. Percival. 1994. Correlation functions estimated from vertical profiles of sediment porosity and compressional wave velocity fluctuations. *EOS*, 75: 202.

Briggs, K.B. and M.D. Richardson. 1994. Geoacoustic and physical properties of near surface sediments in Eckernförde Bay. *Gassy Mud Workshop*, FWG, Kiel, Germany. In press.

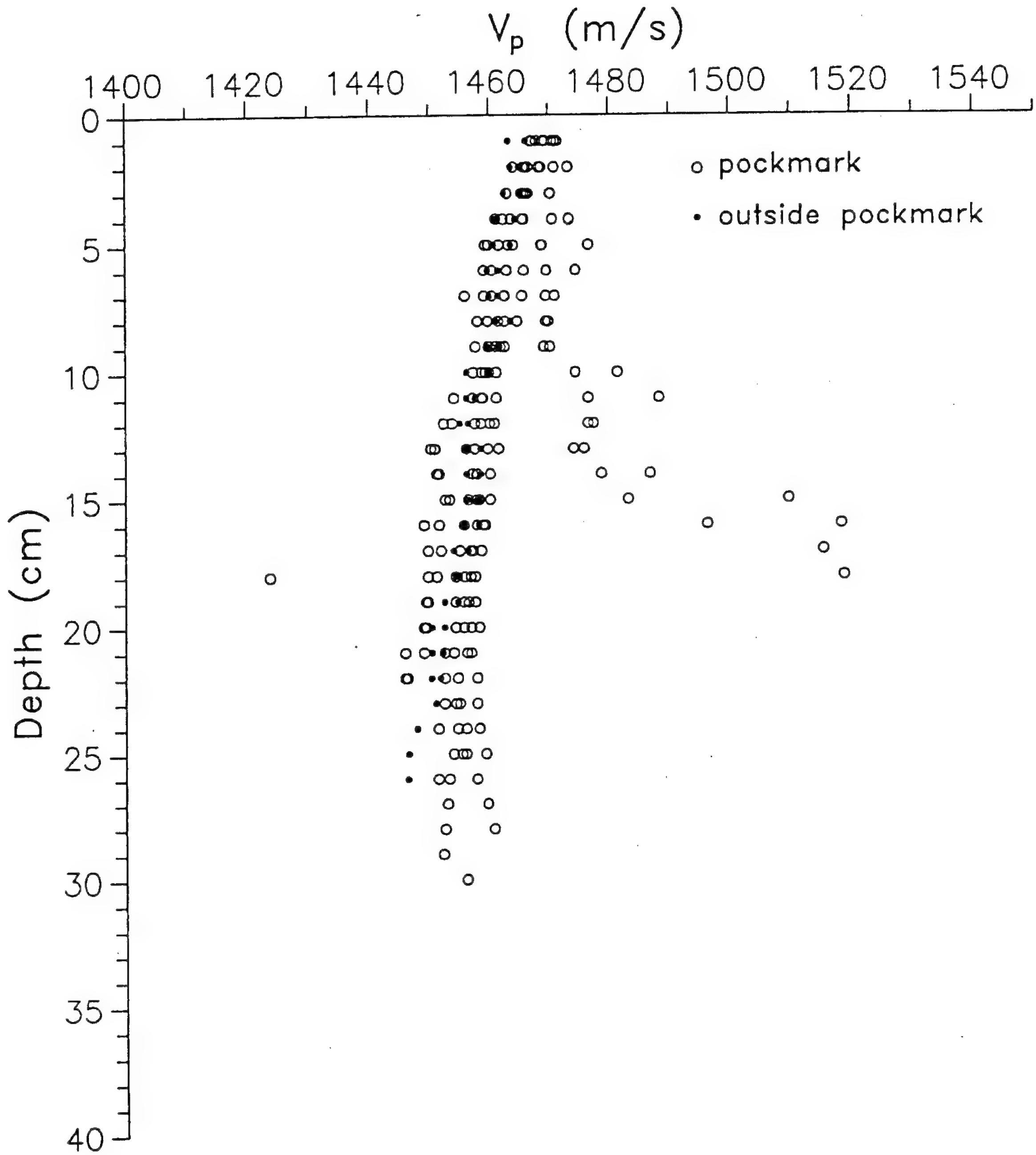
Holyer, R.J., D.K. Young, J.R. Chase and **K.B. Briggs**. 1994. Sediment density structure inferred by textural analysis of cross-sectional x-radiographs and electron microscopy images. *EOS*, 75: 202.

Jackson, P.D., **K.B. Briggs**, R.F. Flint, M.A. Lovell and P.K. Harvey. 1994. Evaluation of the porosity structure of coastal benthic boundary layer sediments using micro-resistivity imaging. *EOS*, 75: 201.

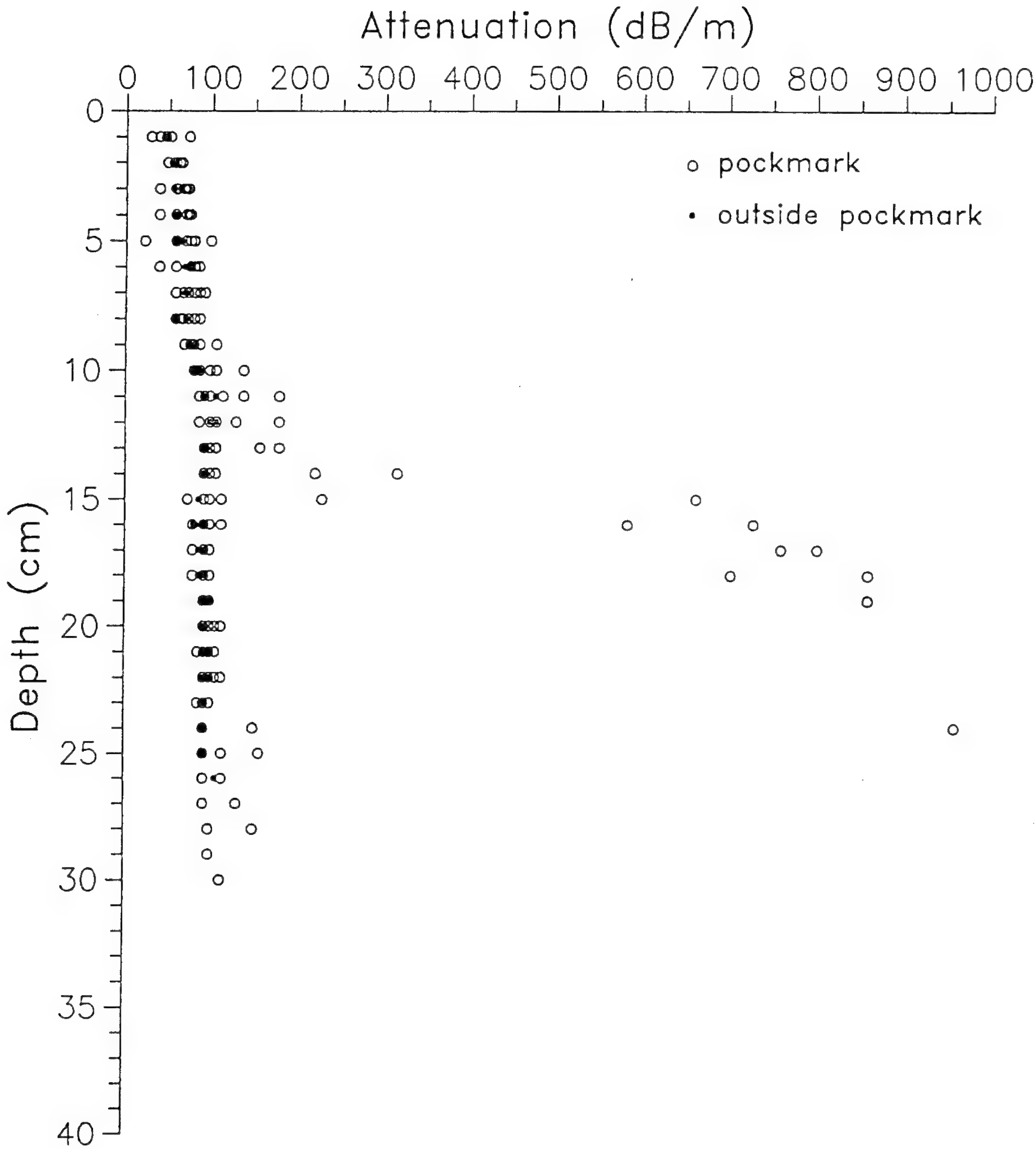
Richardson, M.D., S. Griffin and **K.B. Briggs**. 1994. In-situ sediment geoacoustic properties: a comparison of soft mud and hard packed sand sediments. *EOS*, 75: 220.

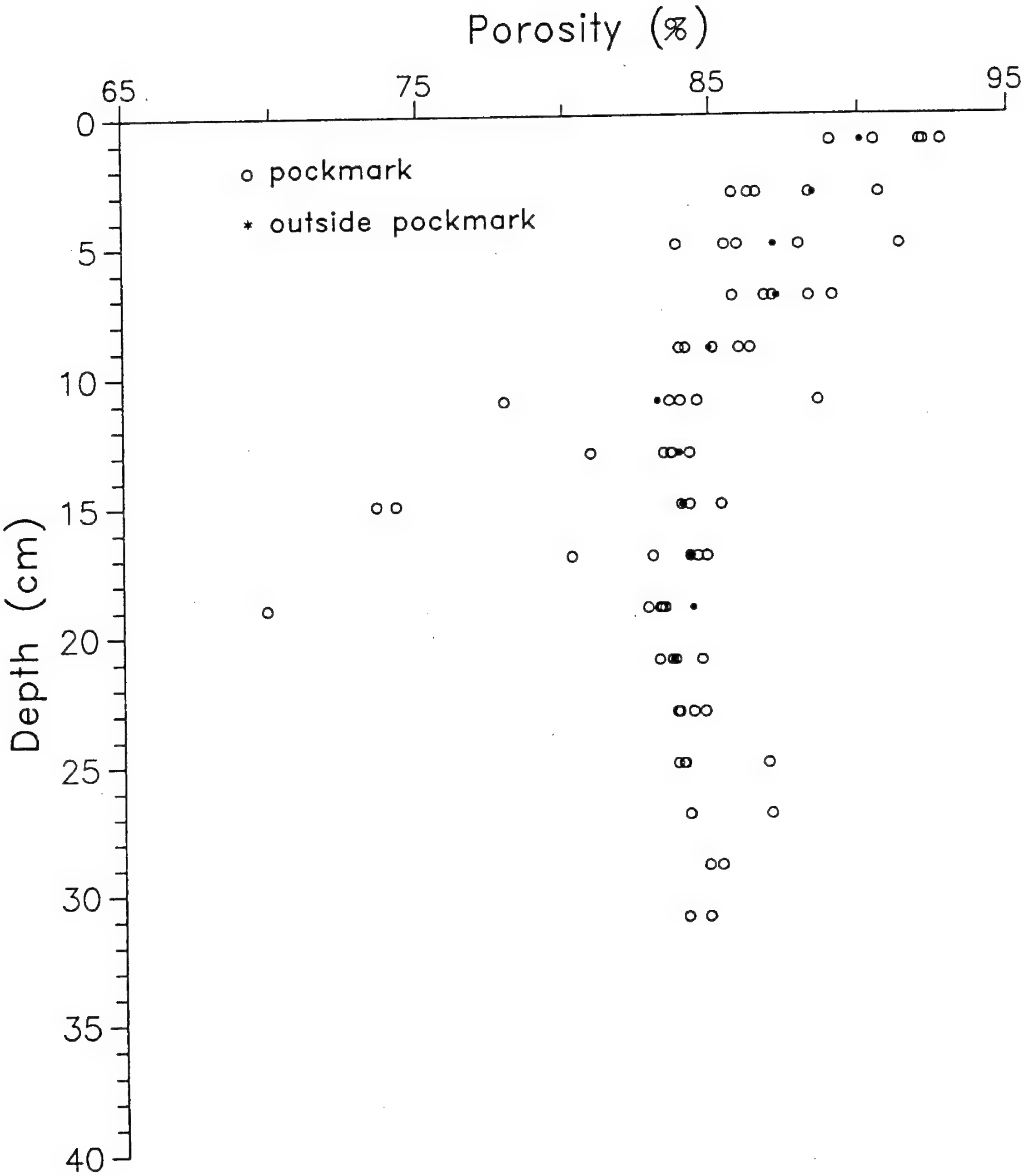
Correlation functions estimated from vertical profiles of sediment porosity and compressional wave velocity fluctuations. AGU-ASLO Ocean Sci. Meeting, 21-25 February 1994, Town and Country Hotel, San Diego, CA.

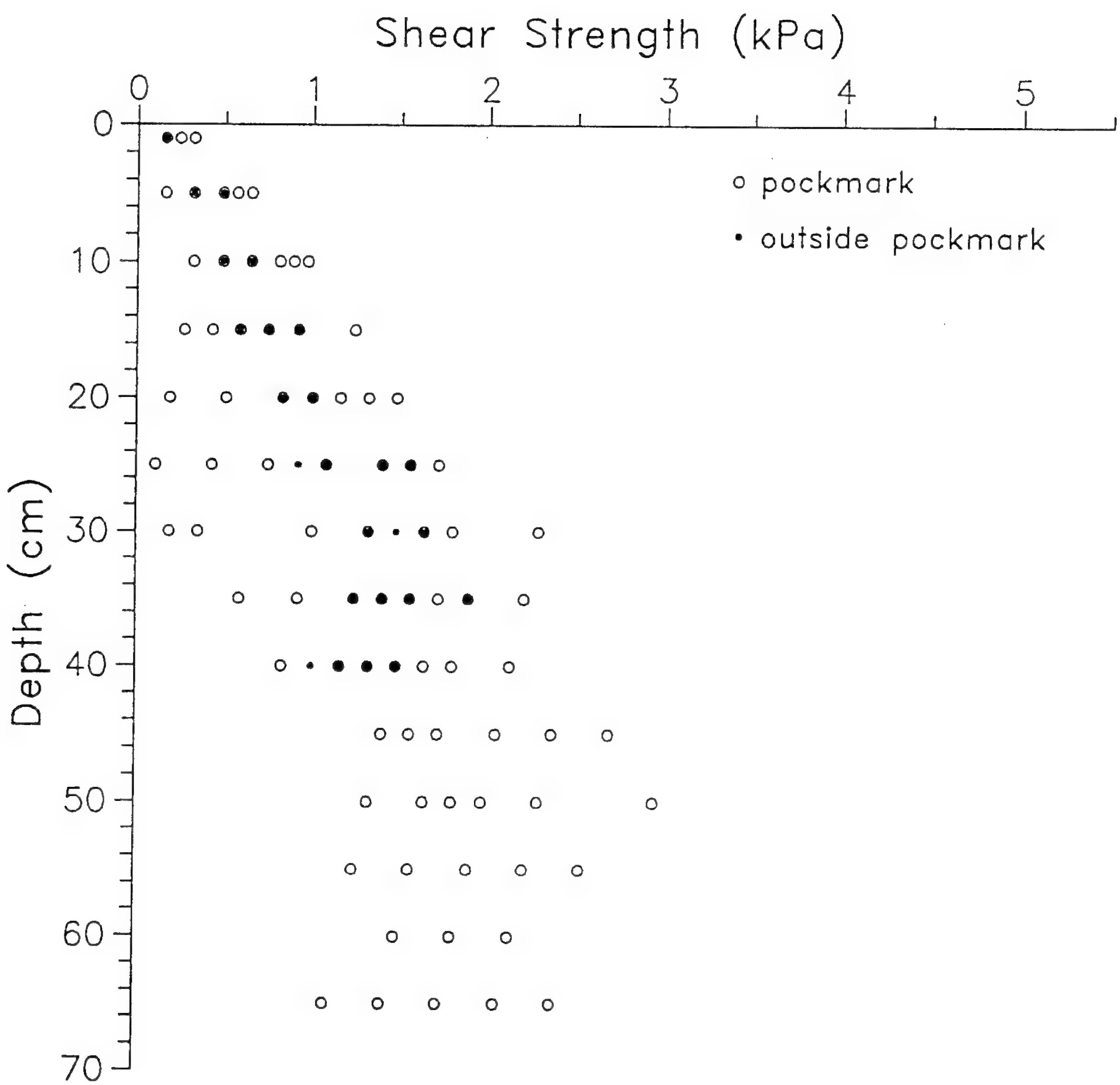
Geoacoustic and physical properties of near surface sediments in Eckernförde Bay. Gassy Mud Workshop, 11-12 July 1994, FWG, Kiel, Germany.

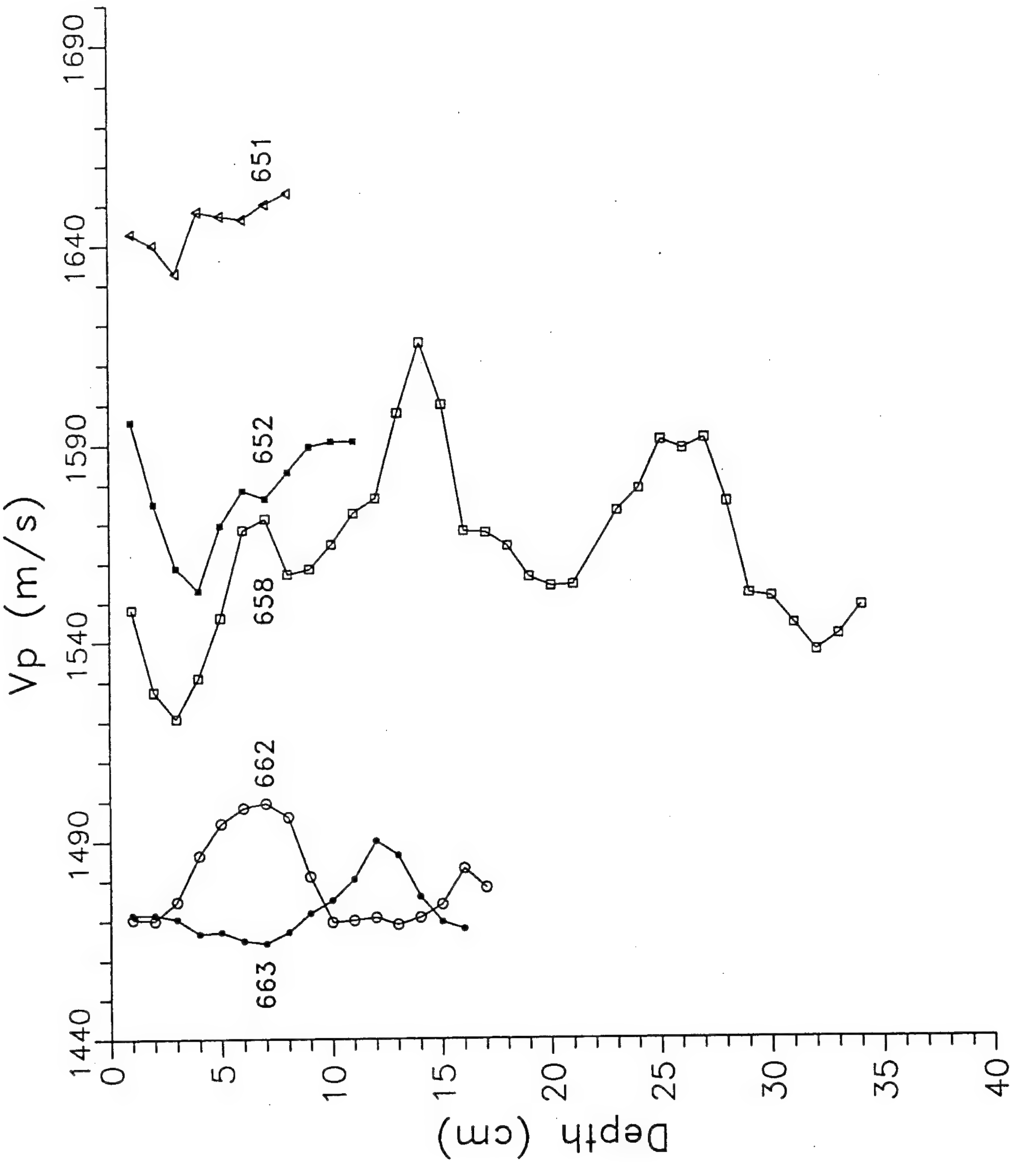


V_p (m/s)
1400
1420
1440
1460
1480
1500
1520
1540
Depth (cm)
0
5
10
15
20
25
30
35
40
o pockmark
• outside pockmark

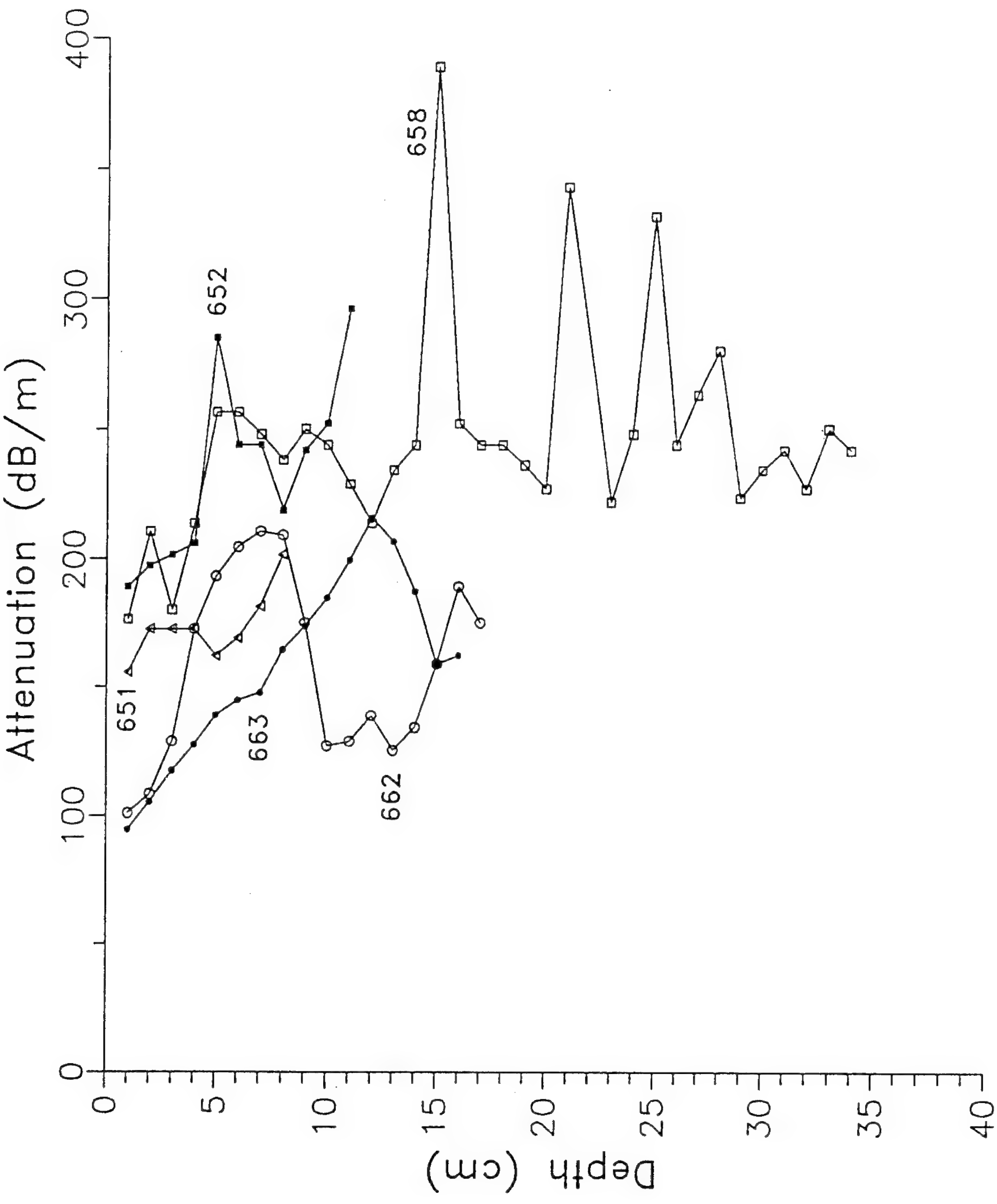

Attenuation (dB/m)
0
100
200
300
400
500
600
700
800
900
1000
Depth (cm)
0
5
10
15
20
25
30
35
40
pockmark
outside pockmark

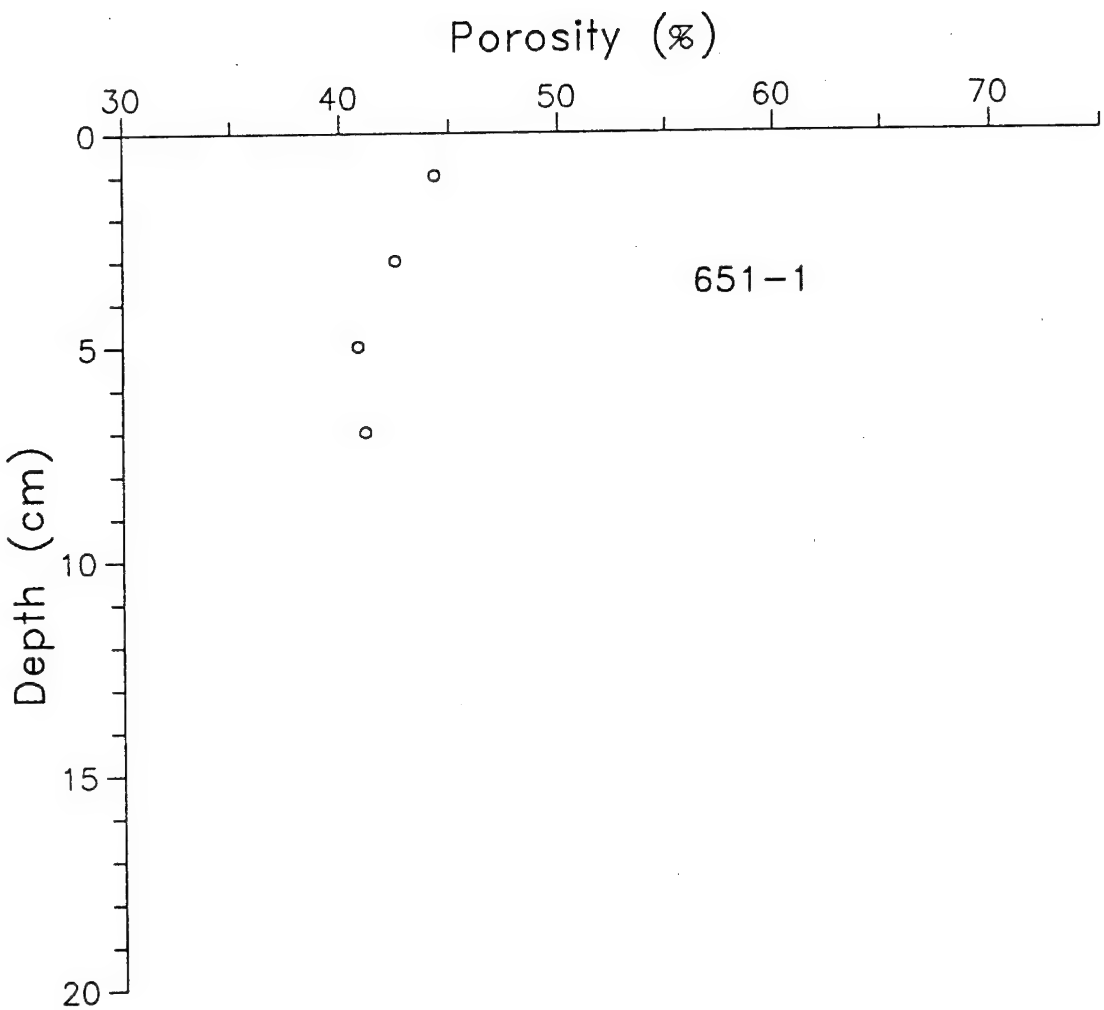

Porosity (%)
65
75
85
95
0
5
10
15
20
25
30
35
40
Depth (cm)
o pockmark
* outside pockmark

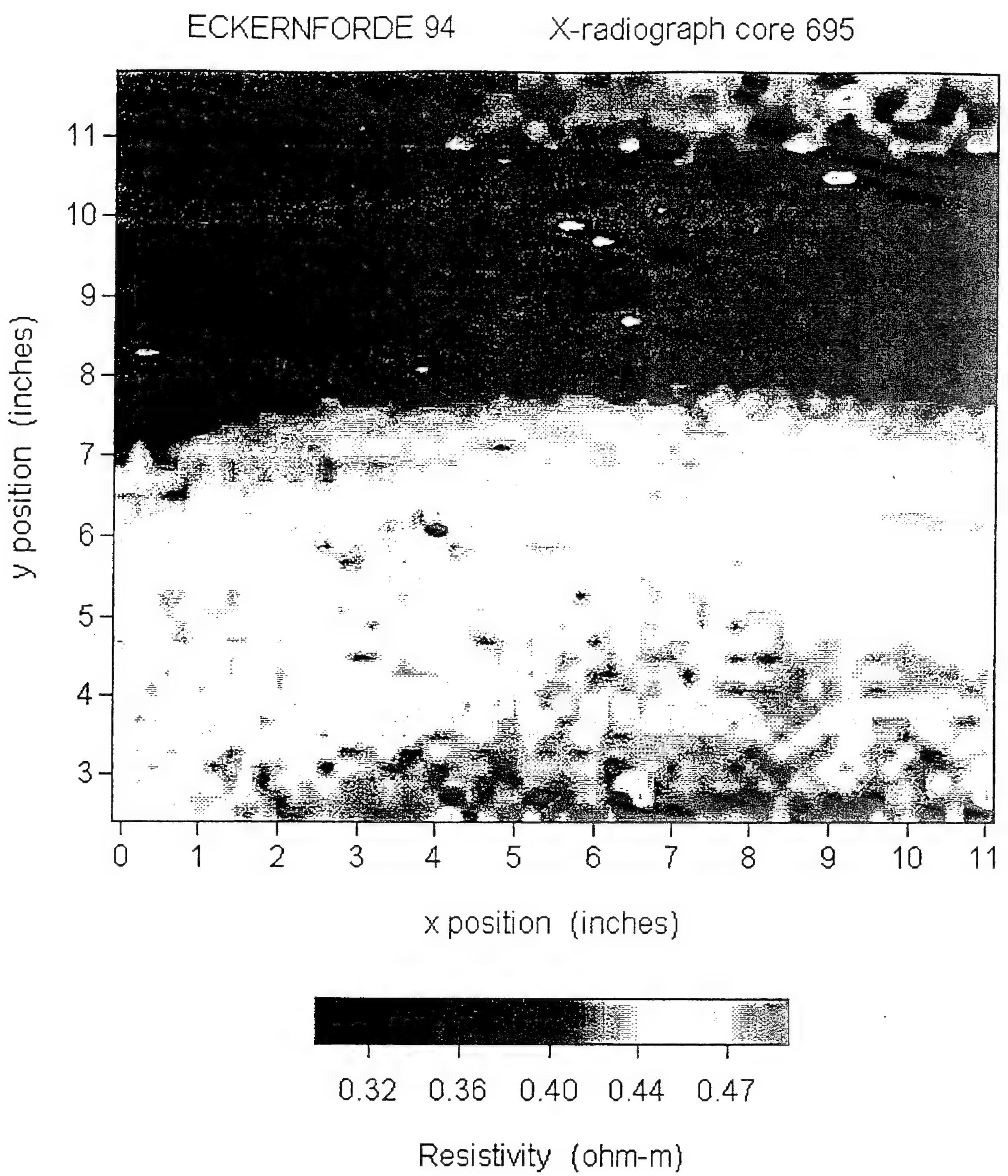

Shear Strength (kPa)
0
1
2
3
4
5
0
10
20
30
40
50
60
70
Depth (cm)
o pockmark
• outside pockmark

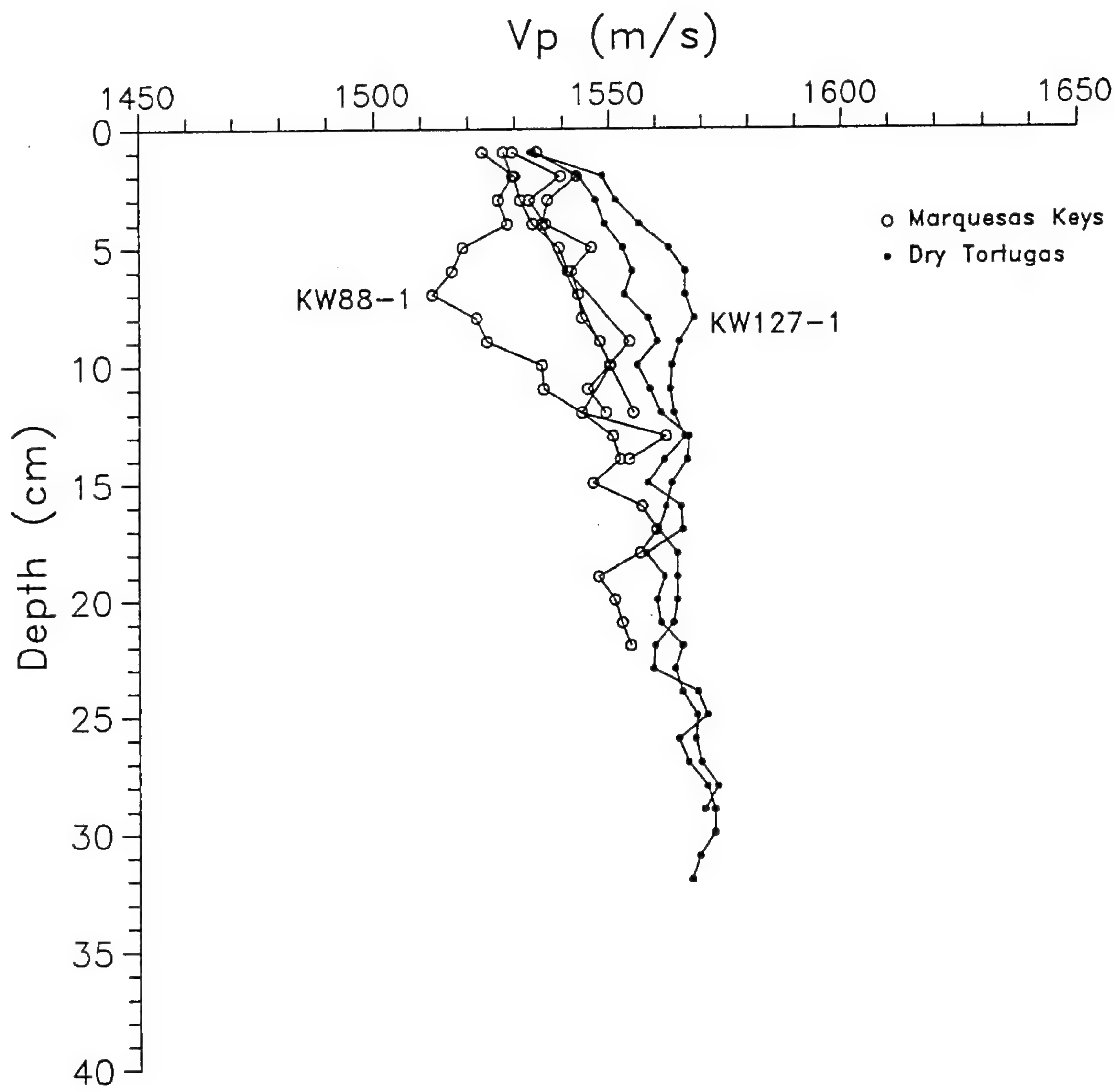


Vp (m/s)
Depth (cm)
1440
1490
1540
1590
1640
1690
0
5
10
15
20
25
30
35
40
651
652
658
662
663

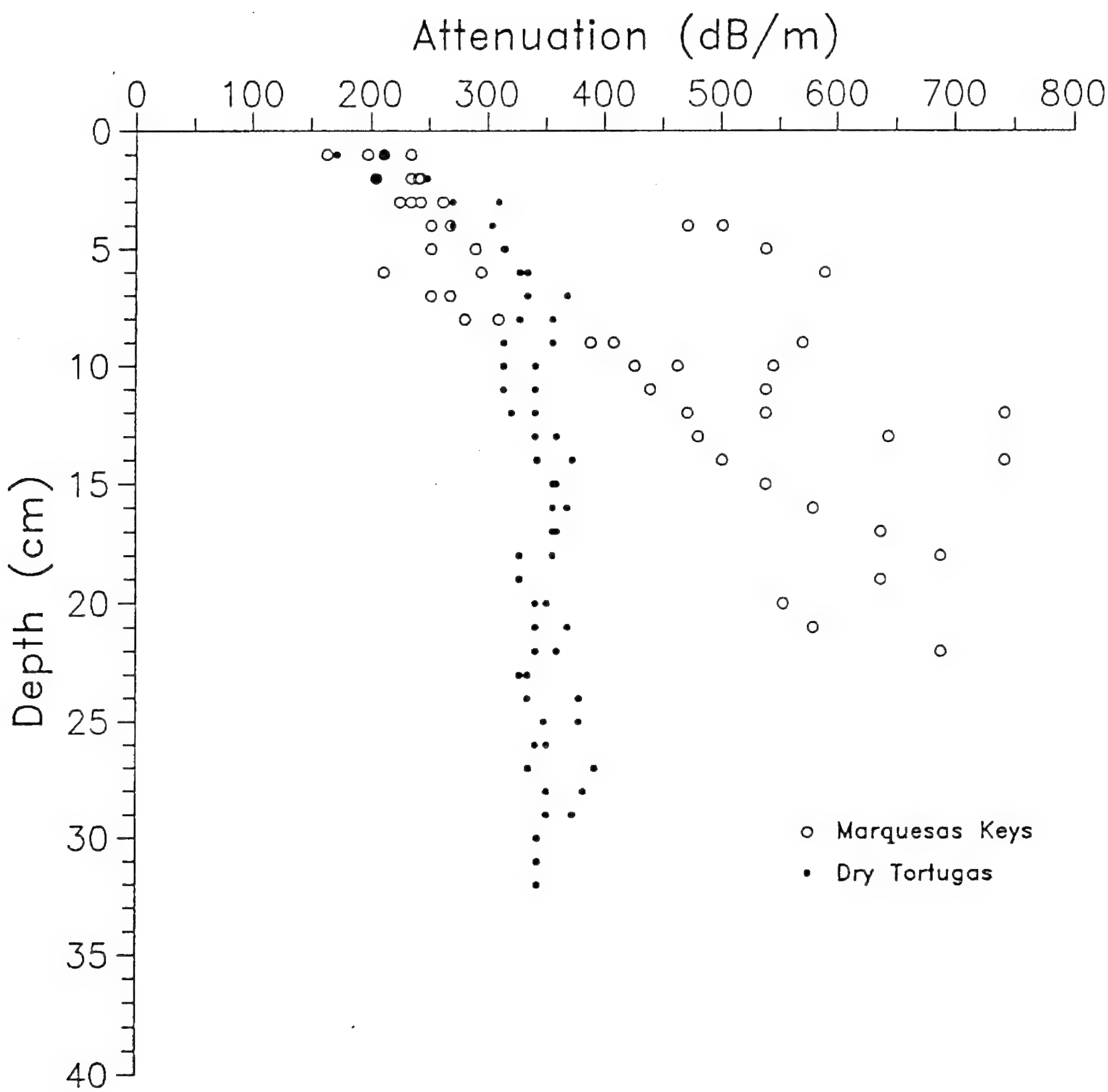

Attenuation (dB/m)
Depth (cm)
0
100
200
300
400
0
5
10
15
20
25
30
35
40
651
652
658
662
663


Porosity (%)
30
40
50
60
70
0
5
10
15
20
Depth (cm)
651-1

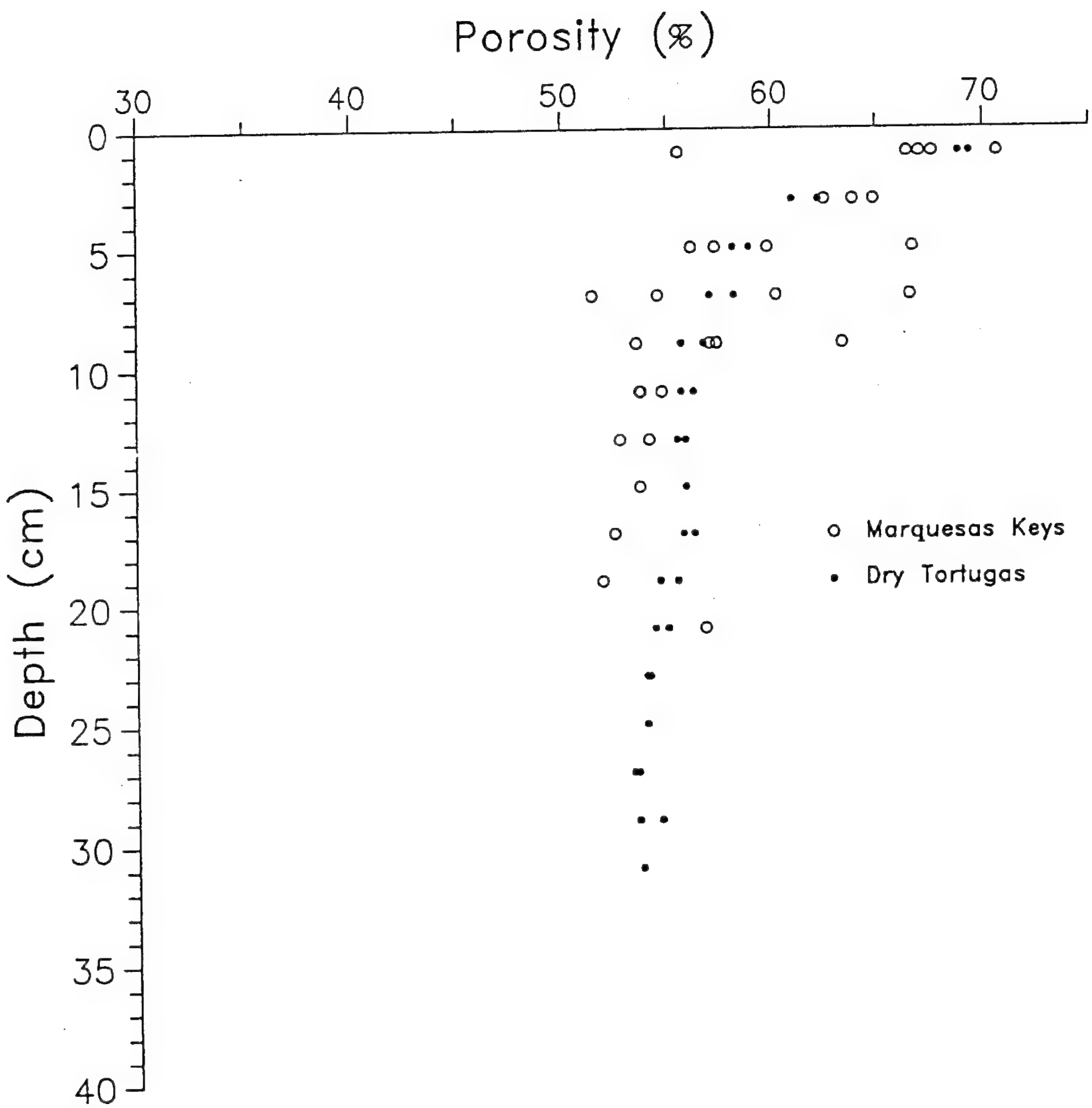

ECKERNFORDE 94
X-radiograph core 695
y position (inches)
11
10
9
8
7
6
5
4
3
0
1
2
3
4
5
6
7
8
9
10
11
x position (inches)
0.32
0.36
0.40
0.44
0.47
Resistivity (ohm-m)



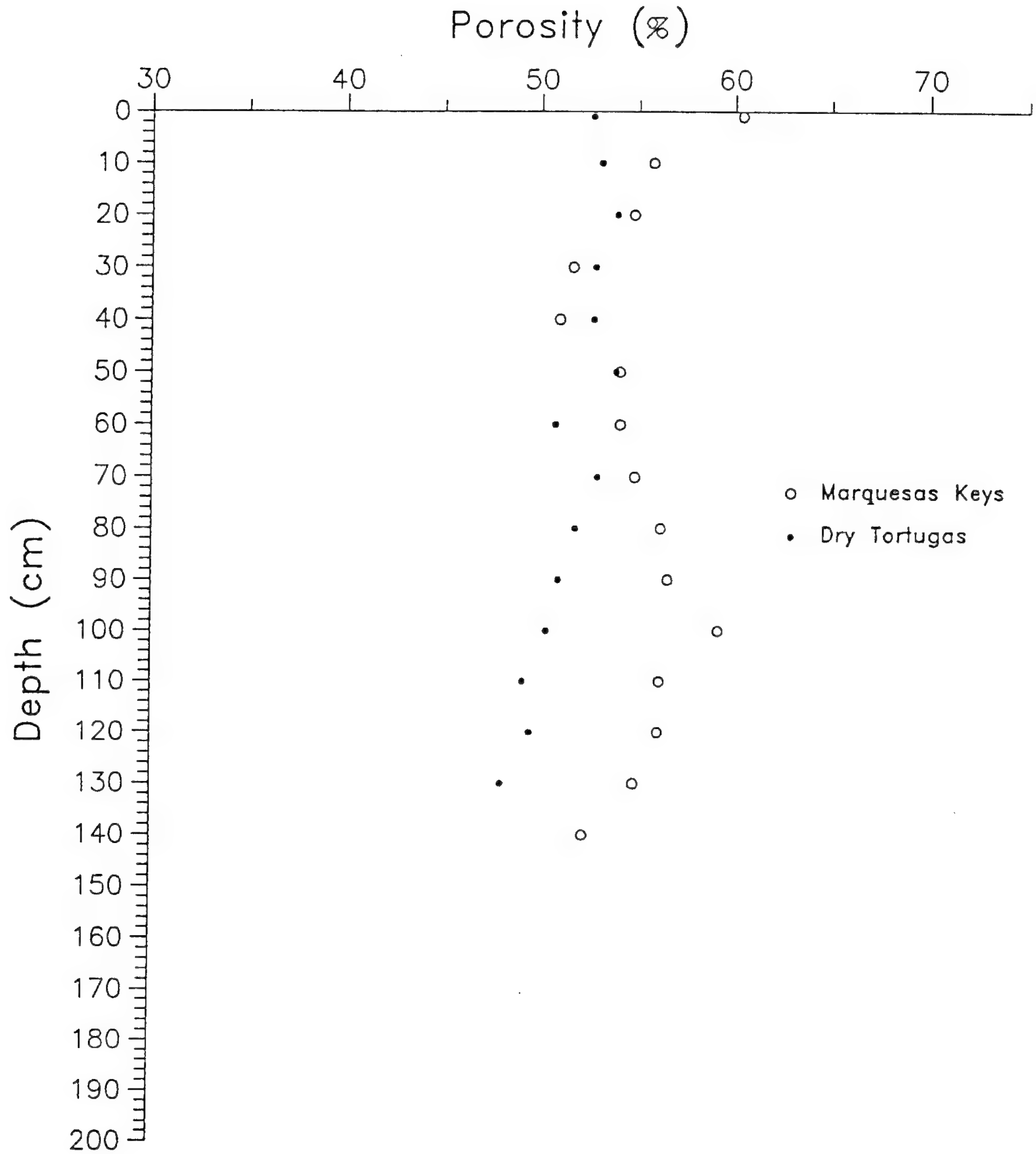
Vp (m/s)
1450
1500
1550
1600
1650
0
5
10
15
20
25
30
35
40
Depth (cm)
o Marquesas Keys
• Dry Tortugas
KW88-1
KW127-1



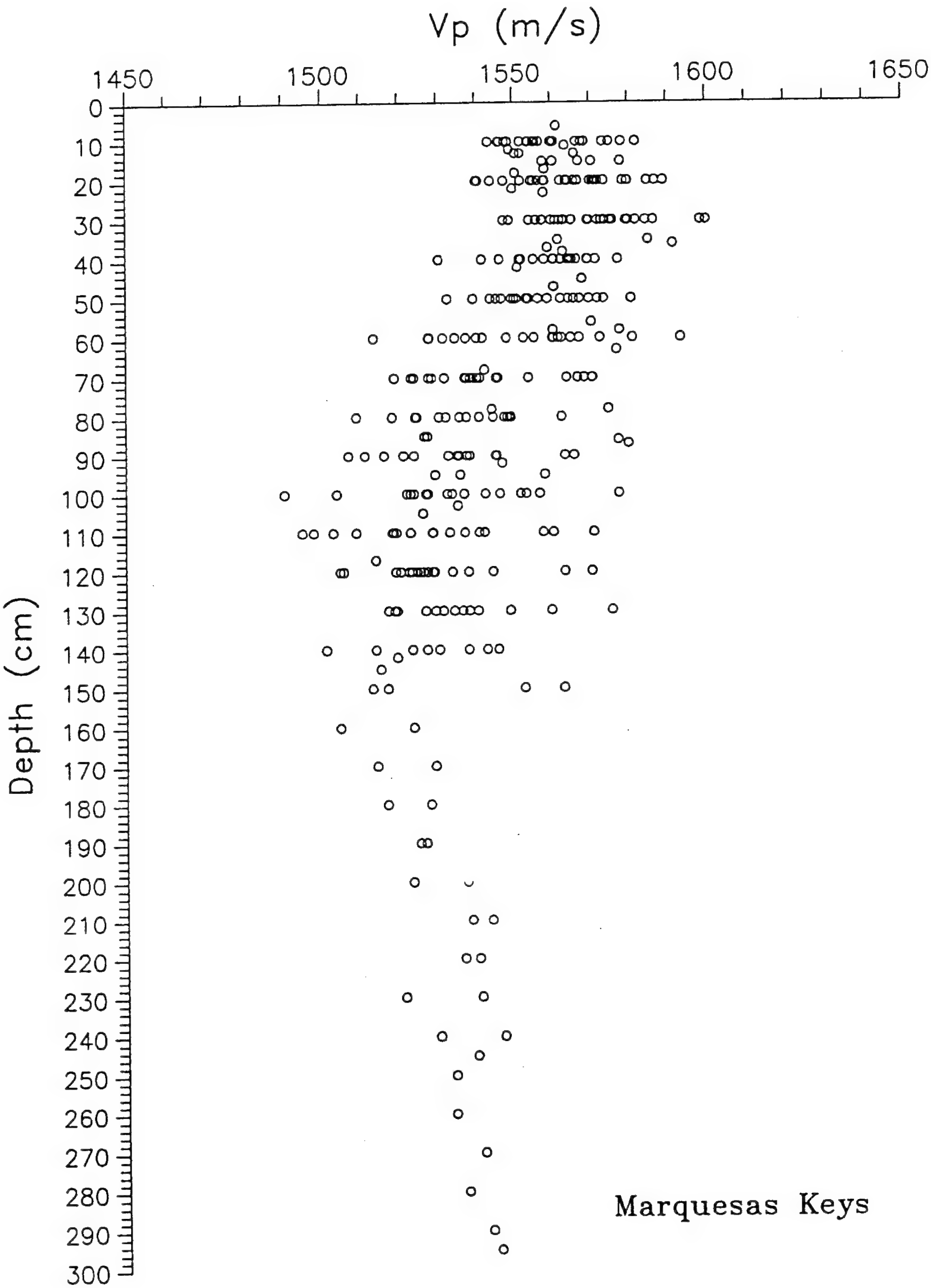
Attenuation (dB/m)
0
100
200
300
400
500
600
700
800
Depth (cm)
0
5
10
15
20
25
30
35
40
Marquesas Keys
Dry Tortugas

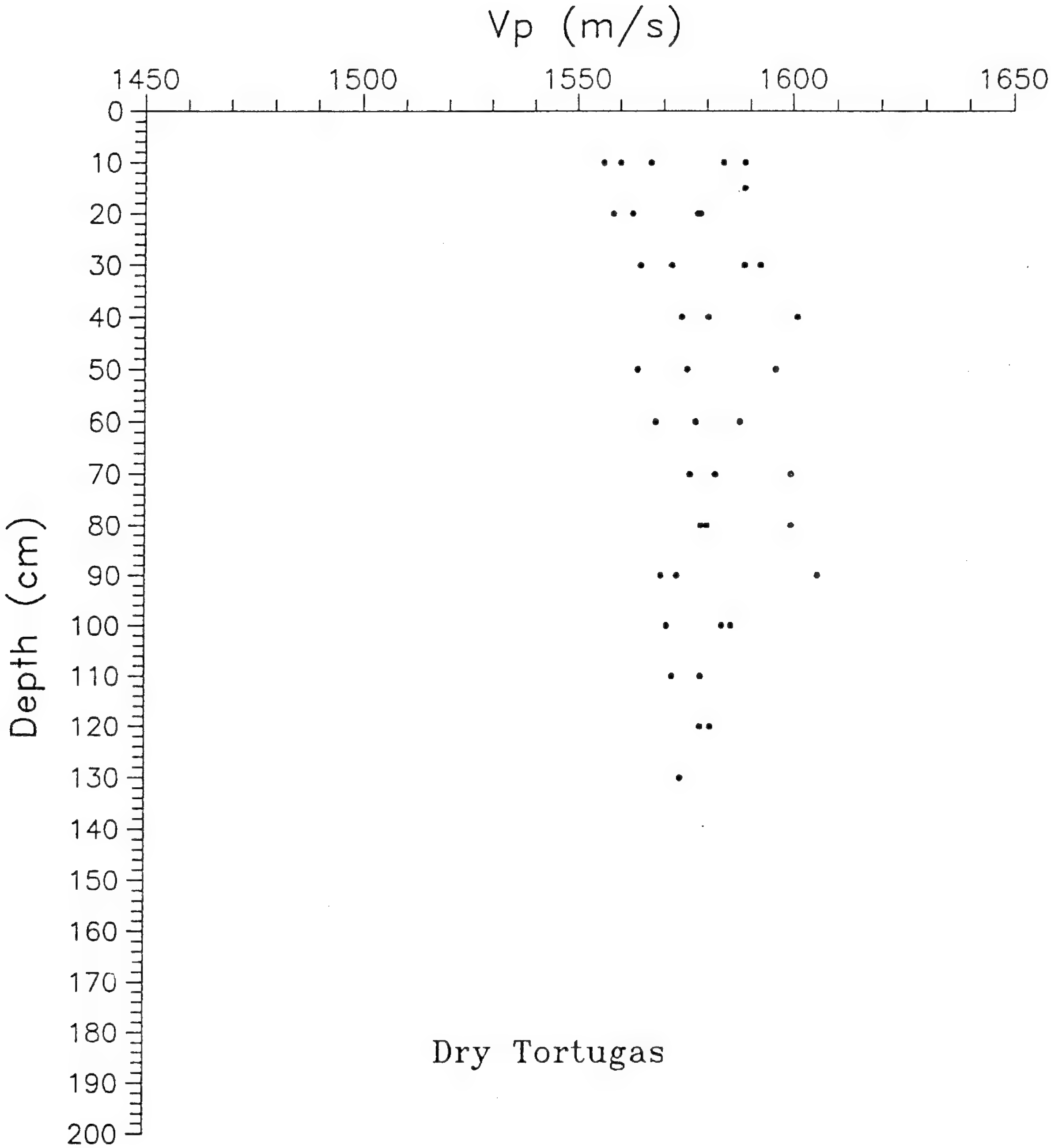


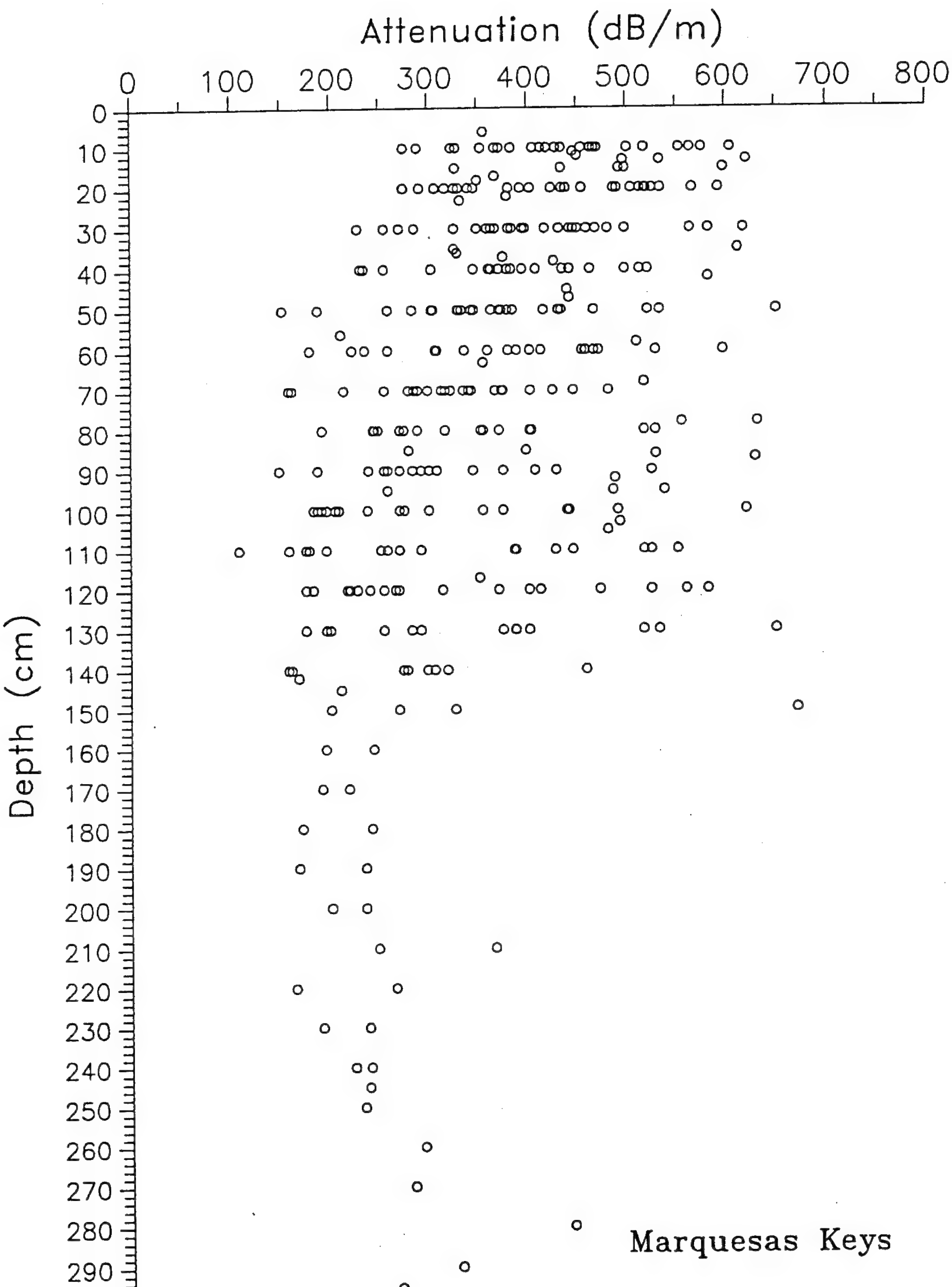
Porosity (%)
30
40
50
60
70
Depth (cm)
0
5
10
15
20
25
30
35
40
o Marquesas Keys
• Dry Tortugas



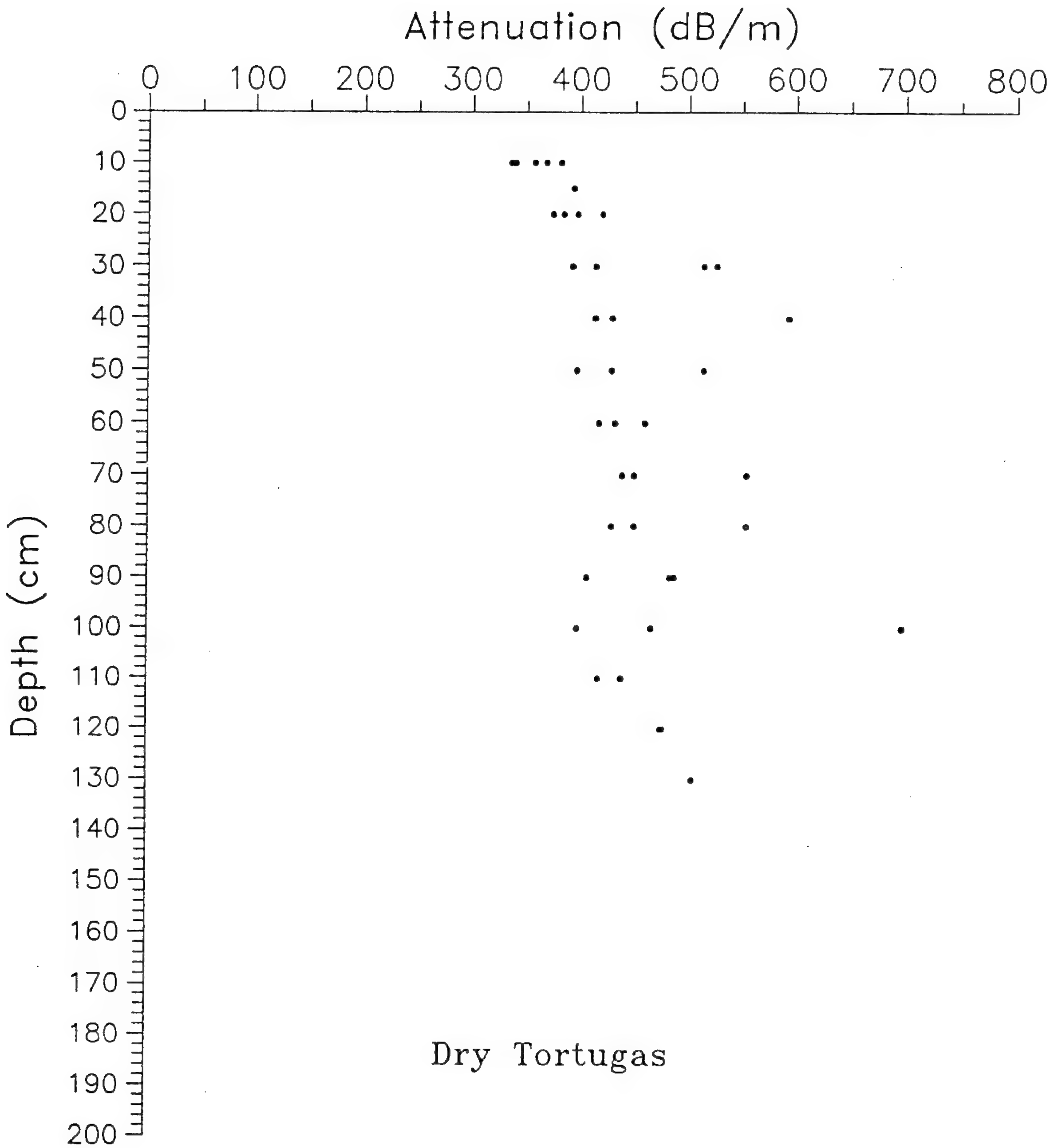
Porosity (%)
30
40
50
60
70
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
Depth (cm)
Marquesas Keys
Dry Tortugas


Vp (m/s)
1450
1500
1550
1600
1650
Depth (cm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
Marquesas Keys


Vp (m/s)
1450
1500
1550
1600
1650
Depth (cm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
Dry Tortugas



Attenuation (dB/m)
0
100
200
300
400
500
600
700
800
Depth (cm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
Marquesas Keys



Attenuation (dB/m)
0
100
200
300
400
500
600
700
800
Depth (cm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
Dry Tortugas

2.4 Processes of Macro Scale Volume Inhomogeneity in the Benthic Boundary Layer (Principal Investigators: W.R. Bryant and N.C. Slowey)

COASTAL BENTHIC BOUNDARY LAYER
SPECIAL RESEARCH PROGRAM
REF: NRL-DET BAA 92-3
PROCESSES OF MACRO SCALE VOLUME INHOMOGENEITY IN THE BENTHIC BOUNDARY LAYER
1993-1994 ANNUAL REPORT

CO-PRINCIPAL INVESTIGATORS
WILLIAM R. BRYANT AND NIALL C. SLOWEY
DEPARTMENT OF OCEANOGRAPHY
TEXAS A & M UNIVERSITY
COLLEGE STATION, TEXAS
77843
409- 854 2680
FAX 409-845 6331

INTRODUCTION

The goals of this project are to understand how and why the physical and geologic properties of the benthic boundary layer vary within various shallow water environments and to relate these variations to the state of stress as a function of time and to the penetration and stability of objects on the seafloor. Specifically, we have been investigating the geotechnical stratigraphy--which includes the density, shear strength (cohesion), porosity, saturation (gas) and sediment component distribution and their three-dimensional structural arrangement--within the boundary layer in more detail than has previously been possible. Sediments of a cohesive nature (clays and silts, clayey sand and sandy clays) and fine-grained carbonate sediments have been investigated. This report reviews our goals, efforts and accomplishments during the first two years of the CBBL SRP.

Our research is based on the premise that the fundamental properties which control both the mechanics of objects and the propagation of compressional waves at the seafloor include the bulk density, shear strength, macro and microfabric and compressibility of sediments. For this reason, the success of efforts to predict the location of objects and then acoustically detect them depends upon our understanding of the spatial and temporal variability of these properties. The largest changes of the bulk density, shear strength and compressibility of sediments within most marine environments typically occur within the upper few meters of the seafloor (the boundary layer). We believe these changes are closely coupled with variations in the texture and structure, the fabric, of the sediments. Based on this hypothesis, we originally proposed to investigate the spatial variability of the physical and geological properties, and the structure of sediments within the boundary layers of select marine environments. Our specific goals have been to characterize this variability (especially vertical gradients) in greater detail than before possible and to determine how the variability in one property relates to that in others. With the aid of other CBBL investigators, our general aim has been to understand how and why variations in seafloor sediment characteristics arise from the dominant physical, biological and chemical processes within the benthic boundary layer.

ACCOMPLISHMENTS

During the last one and a half years, we have put forth considerable effort on behalf of these aims. Much necessary time has been spent organizing, testing equipment, staging and participating in the Eckernförde Bay, Panama City and Florida Keys field efforts; making measurements in the laboratory; analyzing data; and interacting with other project members. For example, aside from daily CBBL activities at Texas A&M, members of our small group have spent over 55 man-days meetings and over 260 man-days working in the field on behalf of the CBBL. The rewards for these efforts are severalfold: we have successfully collected a large number of samples to help us achieve our goals, we have completed analysis of a significant portion of them, we have successfully tested coring devices and collected samples on behalf of several other CBBL investigators, and we have initiated several close collaborations with other investigators to achieve general CBBL objectives.

We collected a suite of gravity cores and box-core subcores containing cohesive sediments from the Eckernförde Bay, Germany, during February and May of 1993. To examine sediment property variability over both macro-scale (mm's to cm's) and micro-morphologic (m's to 100 m's) spatial scales, we are comparing measurements made in the following ways: (1) along transects that extend both horizontally and with depth within individual cores, (2) between gravity cores from the same site and between subcores from the same box core, and (3) between regularly space cores from the same general study area. We have determined the following sediment properties: bulk density, compressional wave velocity, water content, porosity, shear strength (cohesion) and, in some cases, magnetic susceptibility, at spatial intervals of 0.5 to 2.0 cm (Figure 1). Stereo X-radiographs of whole cores and slabs of longitudinally-split cores are being used as indicators of sediment macrostructure. Grain size, grain density, mineralogy and other measurements were made at select intervals. These measurements were made using a multi-sensor core logger, Swedish fall cone, vane shear device, discretely sampled volumes of sediment, pipette analysis, air-compression pycnometer, x-ray difraction, etc. Though tedious, these determinations are now complete (see Table 1), allowing the focus of our efforts with regard to these samples to shift to analysis and interpretation.

Summaries of our analysis of these data has been presented at several meetings (Table 2) and we expect it will lead to publications about benthic boundary layer sediments which are focused on the following themes: (1) detailed relationships and macro-scale variability among the geologic, physical and acoustic properties of the upper 0.5 m of the seafloor; (2) consideration of sediment property variability in the upper 2 m of the seafloor, including time-series analysis of compressional wave velocity and bulk density data to quantify and statistically characterize both macro-scale and micro-morphologic variability; and (3) utilization of stereo X-radiographs to consider the genesis and character of sediment structure and its influence on other properties. To fully achieve our specific goals and broader CBBL aims, we are working together with other CBBL investigators. During the February survey cruise, we tested and evaluated coring equipment on behalf of all investigators and helped geologically interpret the profiles collected during vertical incidence and side scan sonar surveys. During the May cruise, we collected cores on behalf of groups led by A. Anderson of TAMU; C. Martens of UNC; A. Silva of URI; and R. Bennett, D. Lavoie and M. Richardson of NRL.

A member of our group participated in the research cruise on the R/V PLANET to Eckernförde Bay during June and July of 1994. Five 5-meter long gravity cores (Table 1)

We collected a suite of gravity cores and box-core subcores containing cohesive sediments from the Eckernförde Bay, Germany, during February and May of 1993. To examine sediment property variability over both macro-scale (mm's to cm's) and micro-morphologic (m's to 100 m's) spatial scales, we are comparing measurements made in the following ways: (1) along transects that extend both horizontally and with depth within individual cores, (2) between gravity cores from the same site and between subcores from the same box core, and (3) between regularly space cores from the same general study area. We have determined the following sediment properties: bulk density, compressional wave velocity, water content, porosity, shear strength (cohesion) and, in some cases, magnetic susceptibility, at spatial intervals of 0.5 to 2.0 cm (Figure 1). Stereo X-radiographs of whole cores and slabs of longitudinally-split cores are being used as indicators of sediment macrostructure. Grain size, grain density, mineralogy and other measurements were made at select intervals. These measurements were made using a multi-sensor core logger, Swedish fall cone, vane shear device, discretely sampled volumes of sediment, pipette analysis, air-compression pycnometer, x-ray difraction, etc. Though tedious, these determinations are now complete (see Table 1), allowing the focus of our efforts with regard to these samples to shift to analysis and interpretation.

Summaries of our analysis of these data has been presented at several meetings (Table 2) and we expect it will lead to publications about benthic boundary layer sediments which are focused on the following themes: (1) detailed relationships and macro-scale variability among the geologic, physical and acoustic properties of the upper 0.5 m of the seafloor; (2) consideration of sediment property variability in the upper 2 m of the seafloor, including time-series analysis of compressional wave velocity and bulk density data to quantify and statistically characterize both macro-scale and micro-morphologic variability; and (3) utilization of stereo X-radiographs to consider the genesis and character of sediment structure and its influence on other properties. To fully achieve our specific goals and broader CBBL aims, we are working together with other CBBL investigators. During the February survey cruise, we tested and evaluated coring equipment on behalf of all investigators and helped geologically interpret the profiles collected during vertical incidence and side scan sonar surveys. During the May cruise, we collected cores on behalf of groups led by A. Anderson of TAMU; C. Martens of UNC; A. Silva of URI; and R. Bennett, D. Lavoie and M. Richardson of NRL.

A member of our group participated in the research cruise on the R/V PLANET to Eckernförde Bay during June and July of 1994. Five 5-meter long gravity cores (Table 1)

and several diver cores were collected for physical property analysis and stratigraphic interpretation. Analysis of the long gravity cores is now complete and we have begun interpreting the results. In addition, our group member assisted Naval Research Laboratory diving operations and equipment deployment.

We have been working jointly with other investigators in several areas, for example, D. Lambert of NRL to ground truth and geologically interpret normal incidence seismic reflection data, A. Silva of URI to investigate sediment geotechnical properties, D. Young and R. Holyer of NRL to digitally analyze stereo X-radiographs for sediment structure, and R. Faas of Lafayette U to study the time-dependent physical and acoustic properties of fluid muds through laboratory experiments. We expect these and other efforts will lead to joint publications, including several in the special volume of GeoMarine Letters that is being co-edited by one of us.

Members of our small group served the overall aims of the CBBL Special Research Project during the August, 1993, cruise off of Panama City in several ways. We helped make arrangements for the RV Gyre and coring equipment, we acted in the capacity of co-chief scientists to coordinate and satisfy the logistical needs of other investigators, and we contributed to NRL and other diving operations. During the CBBL cruise off of Panama City, members of our a suite of ~90 Shipek grab samples and some short cores were recovered for our own research needs. We suspect that variability in physical and acoustic properties, and side-scan sonar character of the sandy Panama City sediments reflects changes in the size, shape, packing and mineralogy of sediment grains at the sediment-water interface. We are following several approaches to test this hypothesis. First, we have been determining the grain-size distribution (quarter phi intervals) and the percent carbonate of the surface samples we collected and other samples generously provided by colleagues and have been mapping the distribution of these properties throughout the study site. Analysis of most samples is complete and the rest will be done shortly. Distributions of these parameters within the study site are being compared to the side scan sonar and vertical incidence seismic data. To make these comparisons, we have been working together with I. Stender of FWG.

At present we are in the process of starting our study on the fabric of course grained sediments from the Panama City study area. We are now preparing samples by impregnating with L R White which will be serially sectioned at 10 micron intervals. We will be able from this study to determine particle to particle contact area, particle shape, pore size and shape and tortuosity, all the necessary parameters for accurate geoacoustic modeling. The cores used are the ones that have extensive CAT scanning and compressional velocity and bulk

density measured at arc intervals of 45° around and at 0.5 cm intervals down 7 short diver-collected cores. These same cores have been CAT scanned at down-core intervals of 0.2 cm by A. Anderson's group. The orientation of the cores during all measurements is known, so it should be possible to correlate variations in velocity and density to geological characteristics of the sediments imaged by the CAT scanner.

Grain size analyses for approximately 95 Shipek grab samples collected during the August 1993 Panama City, FL experiment have been completed. Sample analysis and calculation of statistical parameters followed the standard methods of Folk (1974). Sediments from the Panama City experimental site can be characterized as fine- to coarse-grained sands (M_z range 0.12ϕ to 5.60ϕ), well sorted to very poorly sorted (σ_i range 0.40ϕ to 3.01ϕ), strongly coarse skewed to strongly fine skewed (SK_i range +0.50 to -0.36), and platykurtic to extremely leptokurtic (K_G range 0.67 to 4.94). Isopleth maps have been constructed of % gravel, % sand, % silt, % clay, mean grain size, inclusive graphic standard deviation, inclusive graphic skewness, kurtosis, and % carbonate content to illustrate the distribution of these properties and their correlation to side-scan sonar backscatter patterns. The data indicate that the distribution of mean grain size values corresponds well with changes in side-scan sonar backscatter patterns on the FWG mosaic. Likewise, variations in the % carbonate component of the sand fraction correlates well with mean grain size distribution and backscatter patterns.

A member of our group participated on the site survey cruise to the Florida Keys (1994) in order to assist NRL investigators. Exploratory samples were collected including 4 diver cores and 35 Smith-MacIntyre grab samples from the study areas off the Marquesas Keys and the Dry Tortugas. Bulk density, compressional wave velocity and CAT scan data have been collected by our group and A. Anderson's group from the diver cores in the same fashion as described for the cores collected in Panama City.

TABLE 1A Analysis of Cores Collected in Germany during February 1993

Core	Length (cm)	Vp	Gamma Density	Stereo X-ray	Shear Strength Vane	Shear Strength Fall Cone	Water Content	Bulk Density
008 BSGC	500	N	N	Y	Y	Y	Y	Y
009 BSGC	500	N	N	Y	Y	Y	Y	Y
010 BSGC	335	N	N	Y	Y	Y	Y	Y
020 BSGC	400	N	N	Y	Y	Y	Y	Y
021 BSGC	218	N	N	Y	Y	Y	Y	Y
022 BSGC	300	N	N	Y	Y	Y	Y	Y
023 BSGC	400	N	N	Y	Y	Y	Y	Y
026 BSGC	500	N	N	Y	Y	Y	Y	Y
028 BSGC	295	N	N	Y	Y	Y	Y	Y
030 BSGC	470	N	N	Y	Y	Y	Y	Y
033 BSGC	368	N	N	Y	Y	Y	Y	Y
035 BSBC	44	N	N	Y	Y	Y	Y	Y
036 BSBC	44	Y	Y	Y	Y	Y	Y	Y
037 BSGC	169	N	N	Y	Y	Y	Y	Y
039 BSBC	46	Y	Y	Y	Y	Y	Y	Y
041 BSBC	48	Y	Y	Y	Y	Y	Y	Y
042 BSBC	42	Y	Y	Y	Y	Y	Y	Y
048 BSBC	48	Y	Y	Y	Y	Y	Y	Y
052 BSBC	26	Y	Y	Y	Y	Y	Y	Y

Notes: Y=completed, N=not completed. Vp and gamma density could not be measured on severely undercut cores were or when pressure and water were lost due to leaking caps.

TABLE 1B Analysis of Cores Collected in Germany during May 1993

	Length		Gamma	Stereo	Shear Strength		Water	Bulk
Core	(cm)	Vp	Density	X-ray	Vane	Fall Cone	Content	Density
206 BSGC	185	Y	Y	Y	Y	Y	Y	Y
207 BSGC	200	Y	Y	Y	Y	Y	Y	Y
208 BSGC	170	Y	Y	Y	Y	Y	Y	Y
217 BSGC	189	Y	Y	Y	Y	Y	Y	Y
218 BSGC	160	Y	Y	Y	Y	Y	Y	Y
219 BSGC	180	Y	Y	Y	Y	Y	Y	Y
220 BSGC	165	Y	Y	Y	Y	Y	Y	Y
306 BSGC	192	Y	Y	Y	Y	Y	Y	Y
308 BSGC	193	Y	Y	Y	Y	Y	Y	Y
311 BSGC	184	Y	Y	Y	Y	Y	Y	Y
316 BSGC	166	Y	Y	Y	Y	Y	Y	Y
317 BSGC	180	Y	Y	Y	Y	Y	Y	Y
320 BSGC	170	Y	Y	Y	Y	Y	Y	Y
321 BSGC	170	Y	Y	Y	Y	Y	Y	Y
326 BSGC	146	Y	Y	Y	Y	Y	Y	Y
327 BSGC	122	Y	Y	Y	Y	Y	Y	Y
330 BSGC	218	Y	Y	Y	Y	Y	Y	Y
331 BSGC	215	Y	Y	Y	Y	Y	Y	Y
332 BSGC	175	Y	Y	Y	Y	Y	Y	Y
334 BSGC	217	Y	Y	Y	Y	Y	Y	Y
336 BSGC	200	Y	Y	Y	Y	Y	Y	Y
337 BSGC	210	Y	Y	Y	Y	Y	Y	Y
338 BSGC	163	Y	Y	Y	Y	Y	Y	Y

Notes: Y=completed, N=not completed. Vp and gamma density could not be measured on severely undercut cores were or when pressure and water were lost due to leaking caps.

TABLE 1C Analysis of Cores Collected in Germany during June-July 1994

Core	Length (cm)	Vp	Gamma Density	Stereo X-ray	Shear Strength Vane	Shear Strength Fall Cone	Water Content	Bulk Density
624 BSGC	431	N	N	Y	Y	Y	Y	Y
625 BSGC	477	N	N	Y	Y	Y	Y	Y
626 BSGC	460	N	N	Y	Y	Y	Y	Y
627 BSGC	472	N	N	Y	Y	Y	Y	Y
628 BSGC	415	N	N	Y	Y	Y	Y	Y

Notes: Y=completed, N=not completed. Vp and gamma density could not be measured on severely undercut cores were or when pressure and water were lost due to leaking caps.

TABLE 2 Project Related Presentations and Publications during 1994

Slowey, N. C., W. R. Bryant, and D. N. Lambert, 1994, The geoacoustic and geotechnical properties of Eckernförde Bay, EOS, Transactions, AGU, v. 75, p. 220.

Davis, K. S., W. R. Bryant, N. C. Slowey, and D. N. Lambert, 1994, Reflections on the geoacoustic and geotechnical characteristics in Eckernförde Bay sediments, Forschungsanstalt der Bundeswehr fur Wasserschall und Geophysik (FWG) Gassy Mud Workshop, Technical Abstracts, Kiel, Germany.

Slowey, N. C. and W. R. Bryant, 1994, Effects of gas and core handling on measurements of compressional wave velocity in ODP Site 893 cores, Scientific Results of the Ocean Drilling Program, v. 146 (submitted).

Bryant, W.R. and A. Anderson, 1994, Gassy marine sediments, Third International Conference on Gas in Marine Sediments, Texel the Netherlands, September 25-28.

Slowey, N. C., W. R. Bryant, and D. N. Lambert, 1994, The geoacoustic and geotechnical properties of Eckernförde Bay, Third International Conference on Gas in Marine Sediments, Texel the Netherlands, September 25-28.

Lambert, D. N., D. J. Walter, W. R. Bryant, N. C. Slowey, J. C. Cranford, 1994, Acoustic prediction of sediment impedance, Acoustical Society of America Annual Meeting in Austin Texas, November 28.

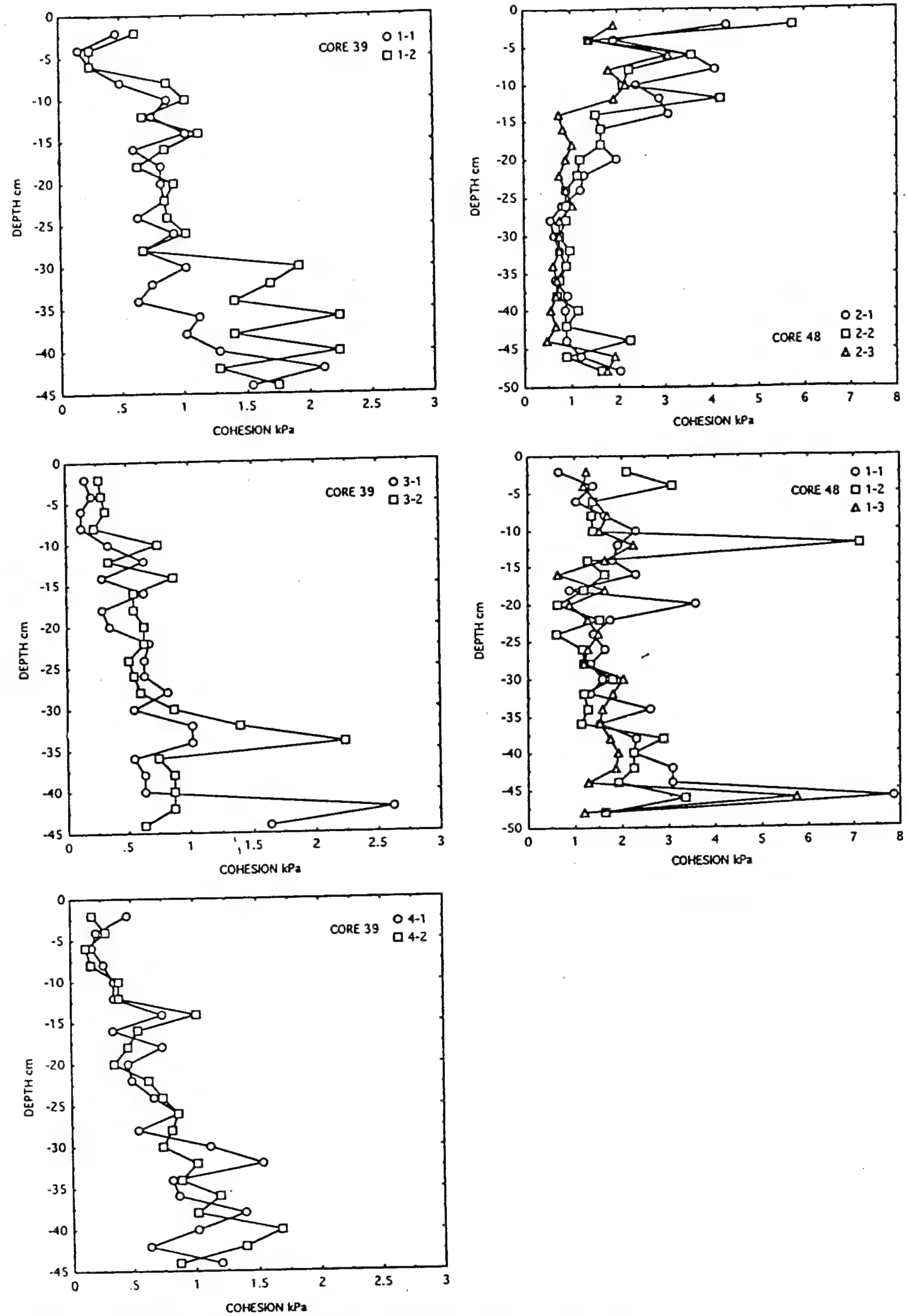


Figure 1. Measurements of sediment cohesion made along transects parallel to the longitudinal axis of several subcores of Box Cores 39 and 48 from Eckernförde Bay.

2.5 Analysis of Seatest Data I (Principal Investigators: N.P. Chotiros, R. Altenberg, S.J. Stanic and T. Kennedy)

ANALYSIS OF SEATEST DATA I

Nicholas P. Chotiros and Robert Altenburg
Applied Research Laboratories,
The University of Texas at Austin
Texas 78713-8029

Stephen J. Stanic and Ted Kennedy,
Naval Research Laboratory
Stennis Space Center
MS 39529-5004

An experiment was conducted by NRL/SSC in cooperation with ARL:UT to measure sound propagation into a sandy sediment. The objective was to study the sound propagation from water into the sediment, in particular, to test the validity of Biot's theory at high frequencies, as part of the Coastal Benthic Boundary Layer SRP.

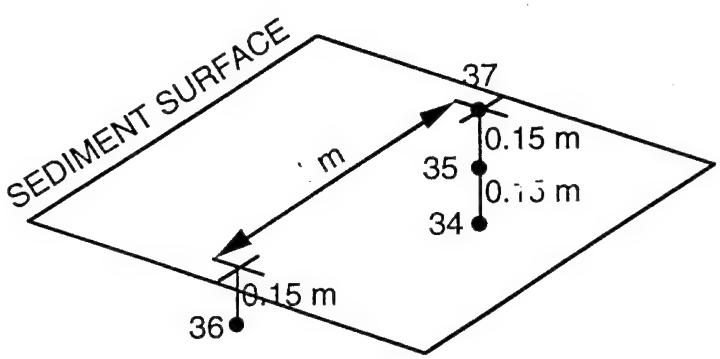


Fig. 1. Configuration of hydrophone array

Experiment:

Based on previous experimental results and knowledge of the geophysics of sandy sediments, a model of acoustic sediment penetration had been constructed. The model was used to estimate the penetration of acoustic waves at frequencies in the high frequency band. Based on these results, a hydrophone array was designed to detect and measure the speed and attenuation of sediment penetrating waves.

A set of acoustic projectors were mounted on a tower at a height of approximately 7 m above the bottom. Three identical hydrophone arrays were planted in a sandy sediment. The configuration of each array is as shown in Fig. 1. Each array consisted of 4 hydrophones: one on the sand surface and 2 others directly beneath at depths 0.15 m (6 in.) and 0.3 m (1 ft). The fourth hydrophone was planted 1 m down range at a depth of 0.15 m. The hydrophones were connected to data collection channels 37, 35, 34 and 36, respectively. Three arrays were placed at ranges 13.7 m, 20.1 m, and 39.4 m from the sound projector, giving grazing angles of 30°, 18.4° and 10°, respectively, as shown in Fig. 2.

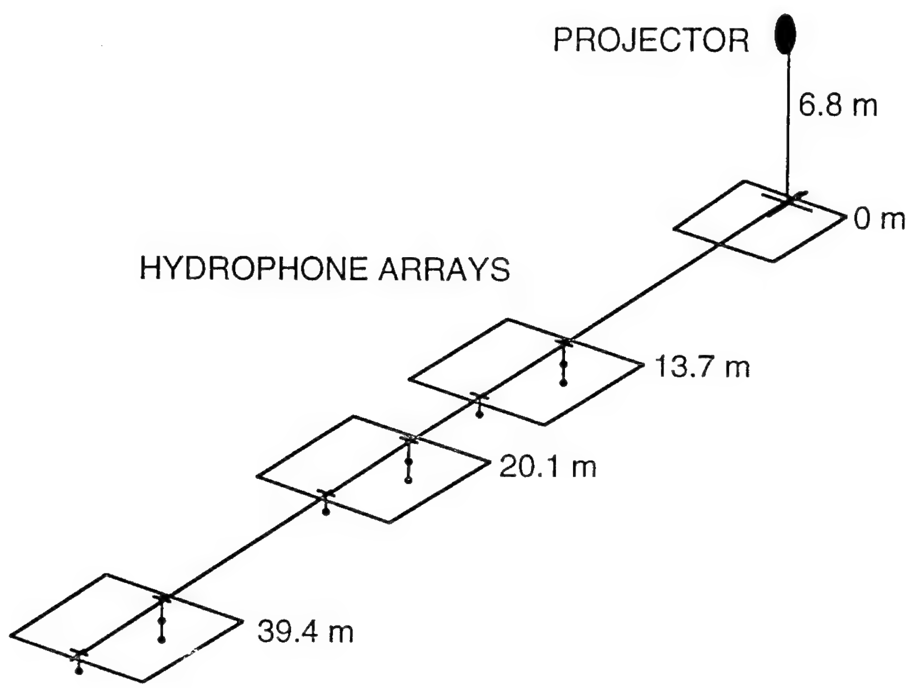


Fig. 2. Bottom penetration experiment

Data processing:

Two types of processing algorithms were applied to the data collected, (1) pulse compression and (2) wave speed and direction estimation. The former was necessary to reduce background noise and sharpen the signal pulses for maximum accuracy in sampling the acoustic energy at each sensor as function of time. The latter uses the compressed pulses to compute the direction and speed of individual acoustic waves.

1. Pulse compression:

The pulses used were typically cw or LFM chirp pulses of a duration between 0.5 ms to 5 ms. The signals were filtered, demodulated to 5 kHz, and sampled at 20 kHz. The recorded data were generally of good quality. Those at the higher frequencies tended to be contaminated by system noise to some degree. An example of the received signals at 110 kHz, from run 313, at the shortest range, is shown in Fig. 3. Two signals are shown. The signal from channel 37 is from the surface hydrophone, and that from channel 36 is from the buried hydrophone 1 m down range. The signals from the buried hydrophones, such as channel 36 tend to be weaker, hence more noisy.

In computing wave direction and speed, it is necessary to be able to accurately resolve the arrival time differences of the signals at the four hydrophones. Normally, phase coherent methods are the most sensitive. However, in an experiment of this type, the placement of the hydrophones will have an error that is typically larger than the signal wave length at these frequencies. Therefore, phase information is not expected to be usable.

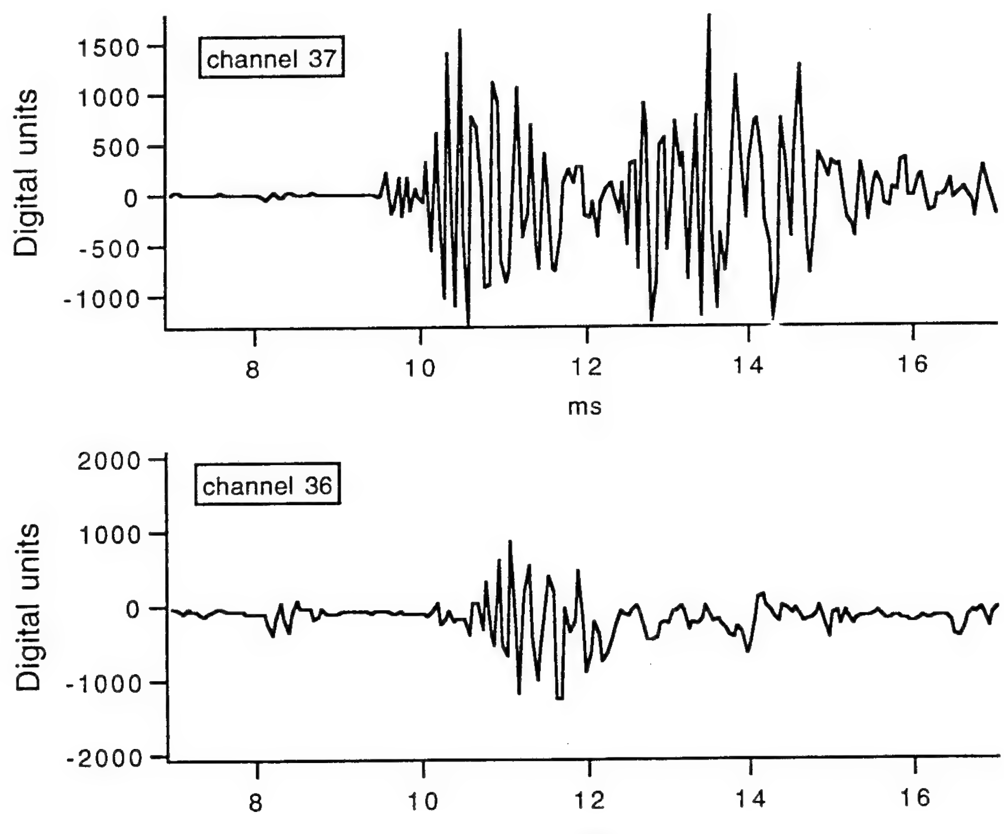


Fig. 3. Raw signals at channels 37 and 36.

Without phase information, the next best approach is to compress the pulse and resolve arrival times with the compressed signal envelope. The usable signal bandwidth is approximately 5 kHz, which should be able to provide a pulse width, hence timing resolution, of 0.2 ms. The signal in channel 37, the surface hydrophone was used as the reference signal; the time of its arrival is defined as t=0. Its FFT was used to construct an inverse filter, which is then applied to the signals from all four hydrophones. The filtered signals were then coherently averaged over a number of pings. Examples of the resulting signal envelope squared are shown in Fig. 4. In this example, the filtered signals were averaged over 10 pings. A pulse width of 0.2 ms was achieved. Furthermore, the improved signal-to-noise ratio permits a timing resolution significantly better than the pulse width.

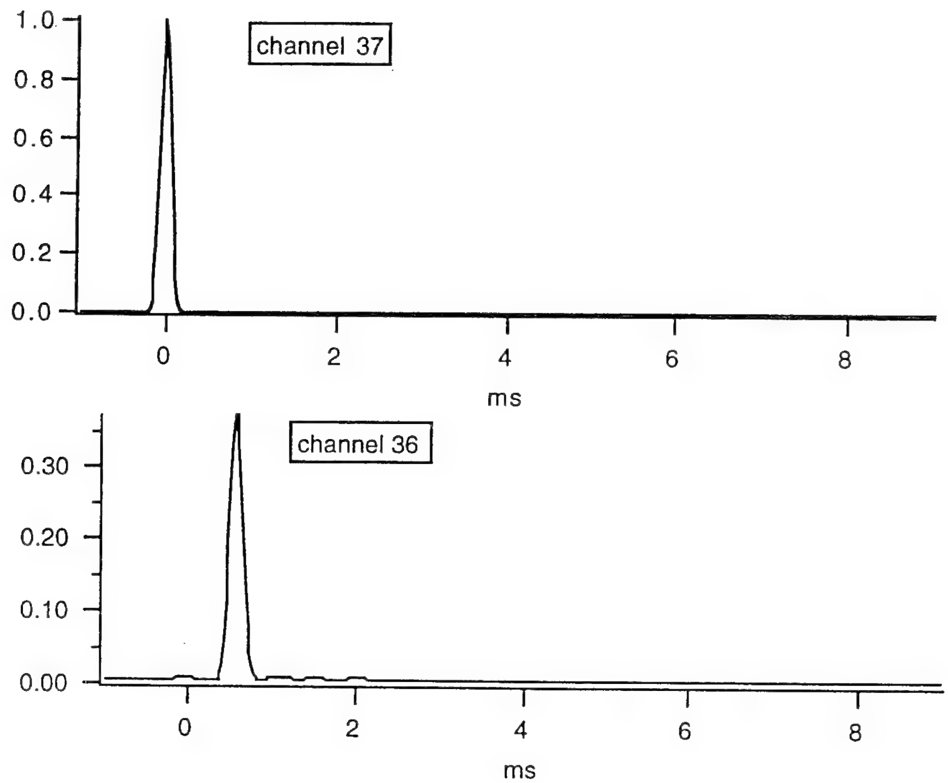


Fig. 4. Detected and pulse compressed signals from first 10 pings of run 313

2. Wave speed and direction

Using a simple linear superposition method, a plot of relative intensity of acoustic waves, as a function of speed and direction was generated for each run. The output is in the form of an

intensity plot in a direction - speed space; direction is in the form of elevation angle, within the vertical section through the source position and the centroid of the hydrophone array, and ranging from +90° (upward vertical) to -90° (downward vertical); the speed range is from 600 to 2500 m/s, in a scale that is inversely linear. A peak in intensity is indicative of a wave traveling at the indicated wave speed and direction. The results from the runs that have been processed so far are shown in Fig. 5.

Runs 298 to 313 cover the frequencies from 20 kHz to 110 kHz at a grazing angle of 30°. It is seen that at the low end of the spectrum, the dominant wave is the fast wave, traveling at a very slight depression angle, at a speed of 1700 m/s. At higher frequencies, a slow wave at a speed of 1200 m/s tends to takeover. At 110 kHz, both waves are detectable. The slow wave, in accordance with Snell's Law, has a steeper depression angle.

Runs 341 to 351 cover a similar range of frequencies. In this case, the slow wave appears to be dominant at all frequencies.

Preliminary Results:

The analysis is still in progress, but a number of statements may be made.

1. At 30° grazing angle, which is very close to the critical angle, both fast and slow waves are detectable.
2. At 10° grazing angle, which is well below the critical angle, the slow wave is dominant.

Presentations:

Nicholas P. Chotiros, Robert Altenburg (Applied Research Laboratories, The University of Texas at Austin), Stephen J. Stanic and Ted Kennedy (Naval Research Laboratory, Stennis Space Center), "High Frequency acoustic penetration of ocean sediments," to be presented at the 128th Meeting of the Acoustical Society of America, 28 Nov. - 2 Dec. 1994.

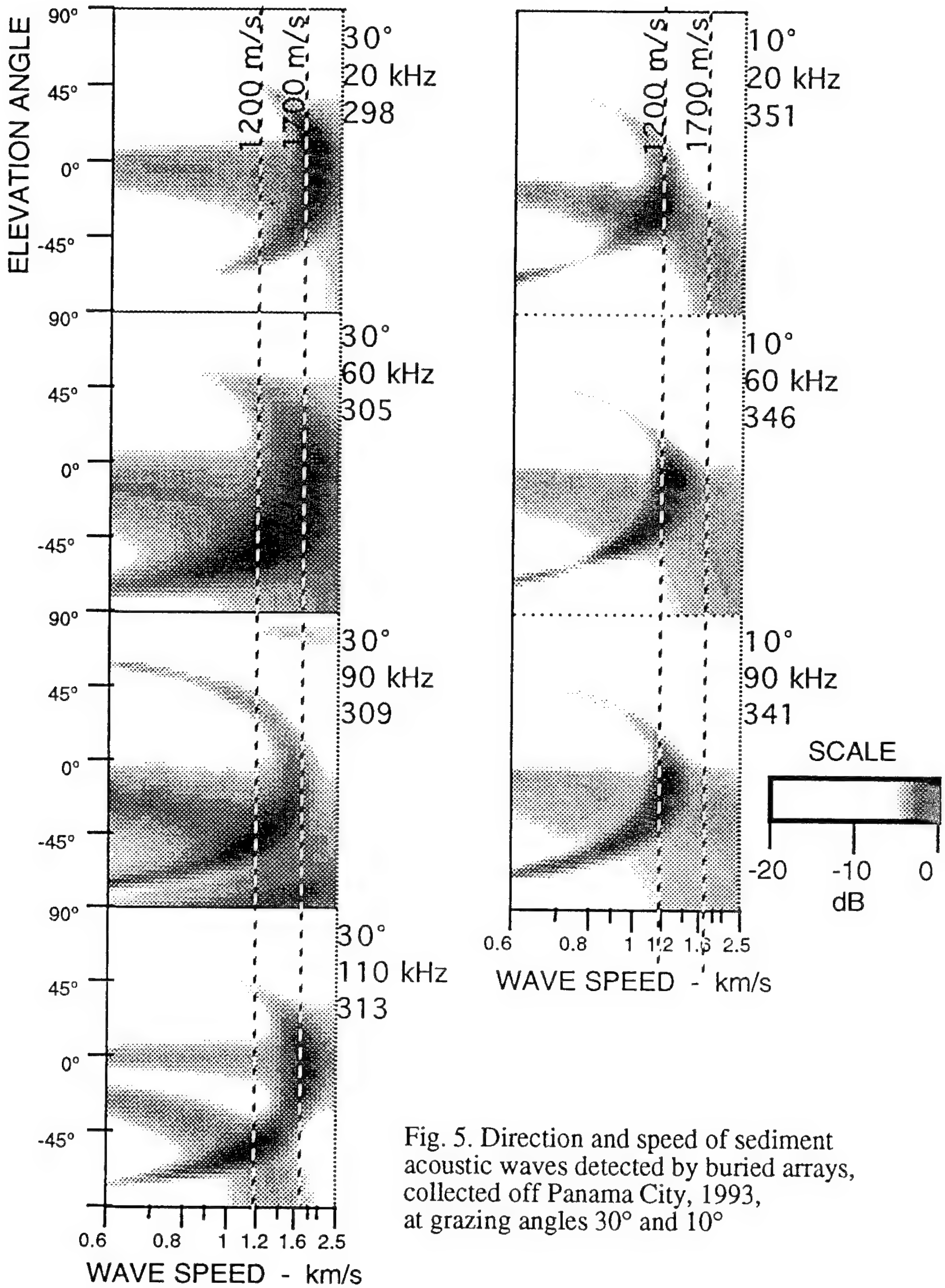


Fig. 5. Direction and speed of sediment acoustic waves detected by buried arrays, collected off Panama City, 1993, at grazing angles 30° and 10°

2.6 Geophysical Measurements for the In Situ Determination of Seabed Sediment Geotechnical Characteristics (Principal Investigators: A. Davis, D. Huws and R. Haynes)

Geophysical Measurements for the In Situ Determination of Seabed Sediment Geotechnical Characteristics (Principal Investigator: A M Davis, UCNW)

CBBLSRP FY94 YEAR-END REPORT

Angela Davis, Dei Huws and Ron Haynes
School of Ocean Sciences
University College of North Wales
Menai Bridge LL59 5EY, UK

PROJECT OBJECTIVES

For the UCNW team the major project goals were:

i). to assess the extent to which newly developed UCNW geophysical technologies could be relied upon to provide quantitative information on seabed properties within the area under investigation,
ii). to investigate the spatial variability of the measured geophysical quantities: electrical resistivity, shear wave velocity and seismic reflection attributes (acoustic impedance, compressional velocity, reflection amplitude etc.), and
iii). wherever appropriate and with reference to other site data and control information, to further interpret the geophysical data to provide specific information on the geotechnical characteristics of the sea floor materials.

UCNW's experiments which were conducted from the PLANET resulted in a series of interdependent geophysical data sets which are currently being processed and interpreted at the University's laboratories in Menai Bridge. This report summarises the preliminary findings and outlines the scope of the work in the context of the CBBL Special Research Program.

BACKGROUND

UCNW's contribution to the CBBLSRP arises from research carried out over many years aimed specifically at improving the understanding of geophysical-geotechnical property relations. The various research approaches have included:
(i). laboratory testing:- simultaneous measurement of geophysical and geotechnical quantities under controlled conditions,
(ii). theoretical and empirical modelling:- to allow predictions of sediment behaviour under varying stress conditions, and
(iii). development of new marine geophysical survey methodologies:- to allow *in situ* sensing of the physical properties of sea floor sediments.

Within the CBBLSRP, the University's effort is being directed towards *in situ* measurement, aiming to provide physical property data using underway approaches. Seismic shear wave velocities which are being measured with a specially developed bottom-towed geophysical sled (Davis et al. 1989), are known to be indicative of a material's structural strength and will likely be used to make inferences on the sediment's engineering behaviour under varying stress conditions; electrical resistivities, measured simultaneous with the

shear wave velocity, are dependent on the properties of the pore space and will be used to supplement the geophysical interpretation. As both quantities are being acquired in 'mapping mode', they will also be able to provide information on the spatial variability of the sea floor sediment properties (Huws et al. 1991). Using a separate underway approach, UCNW are also contributing physical property data through seismic sub-bottom profiling experiments. High resolution reflection data are being acquired in digital format ready for advanced signal processing and 'geotechnical' analysis. The final analysis, which effectively converts the seismic section to a physical property section, relies heavily on theoretical and empirical interrelationships (Haynes et al. 1993).

The ability to provide a quantitative description of the seabed sediment properties using underway geophysical techniques will have obvious benefits for the CBBLSRP. For instance, it will enable single-point static measurements to be extrapolated to cover a larger area, it will provide a rapid reconnaissance approach to geotechnical site characterisation and physical ground-truthing, and it will provide useful input data for geoacoustic model validation exercises. Adopting the UCNW approach it should be possible to provide important information on metre and kilometre sized features and especially on the spatial variability of these features and through this, it should be possible to provide valuable insights into the effects of biochemical, geological and hydrodynamic processes on larger scale sediment structure. In addition and aside from this, the CBBLSRP has provided the University with a unique opprtunity to ground-truth its own geophysical survey methodologies.

ECKERNFOERDE EXPERIMENT

UCNW's experimental programme was designed to capitalise on the wealth of information provided by other researchers participating in the CBBLSRP. The measurements most directly comparable to UCNW's are those of RD Stoll and MD Richardson for shear waves, KB Briggs and PD Jackson for electrical properties, and DN Lambert and SG Schock for high resolution reflection profiling.

Geophysical Sled Measurements

Measurements with the UCNW bottom-towed geophysical sled (the 'magic carpet') were carried out on selected trial sites in Eckernfoerde and Kiel Bays (fig. 1). The main components of the sled are shown in fig.2, with further information on the system and on operational procedures contained in Davis et al. 1989, Davis et al. 1991, and Huws et al. 1991. During 3 separate deployments of the 'magic carpet' in 3 different sedimentary environments, a total of 302 shear wave records were collected and 200 electrical resistivity readings made. Measurements were made either with the ship drifting in the wind, or with the vessel underway making approximately 0.5 to 1 knot over the ground. The distance between geophysical sampling points was typically 20-25 metres. Figure 1 shows the location of survey tracks and provides information on sea floor sediment distribution. Each seismic record, which comprises a series of signal traces resulting from a single shot with the shear wave source (see fig.3 for an example record), is inverted to provide information on the velocity structure (using a standard refraction analysis - see fig.4)

at the measurement location. Measurements of the sediment electrical resistivity were taken simultaneous with shear wave travel times, and the values converted to an equivalent formation factor through input of a seawater resistance reading.

Sub-bottom profiling
Seismic sub-bottom reflection profiling was carried out independent of the shear wave/ electrical resistivity survey, along lines which had previously been surveyed using a Chirp sonar system and the NRL Acoustic Sediment Classification System, ASCS (see fig. 1 for location of UCNW survey tracks). During part of the survey the ASCS was run in parallel with the UCNW profiling system to provide simultaneous output for a rapid visual comparison of data during recording, and for subsequent systems evaluation.

An EG&G Uniboom seismic source was used to generate seismo-acoustic energy. The Uniboom was chosen for its high repeatability of signal generation and the broadband nature of the pulse (typically 400Hz to 10kHz). High resolution single and multi-channel digital seismic reflection data were recorded with either a single element hydrophone or a newly developed multi-channel streamer coupled to a multi-channel digital seismic acquisition system. The multi-channel streamer, comprising 12 single element transducers at 1 metre spacings, was designed and constructed in the University's laboratories by Dr Jim Bennell. The acquisition system hired in for this survey was a Marine Geophysical Systems' MDAS, a system which is designed specifically for very high resolution work i.e. designed for very rapid sampling of the seismic waveform (minimum sampling rate of 30kHz, typically 40kHz). This level of sampling is required for a 'geotechnical' analysis of the seismic reflection response.

RESULTS

On the basis of the preliminary interpretation (based on a subsample of UCNW's data set), it is possible to draw some broad conclusions on the geophysical character and related geotechnical properties of the sediments of Eckernfoerde and Kiel Bays.

Shear waves
As can be seen from fig.1, the shear wave tracks traversed a variety of surface lithologies. The initial survey (line 1) was concentrated in the NRL test-bed site, to the southwest of Mittelgrund, to provide additional geophysical ground-truth information on the gassy mud. Line 2, lying along the north east edge of the Mittelgrund, traversed a series of core locations and sites which had been previously investigated with the NRL ISSAMS probe. Line 3, lying due north of Mittelgrund and outside of Eckernfoerde Bay in Kiel Bay, was chosen for its highly variable lithologic character in order to assess the extent to which the methodology could be relied upon to provide quantitative information on the physical properties of a spatially heterogeneous sea floor. The physical nature of the seabed materials in the vicinity of line 3 were already well known, the area having been extensively surveyed during a previous CBBLSRP seabed classification experiment.

To assist the choice of data for the preliminary interpretation reference was

made to published sediment distribution maps (Seibold et al. 1971) and to ASCS data collected simultaneous with the sled measurements. With access to this information it proved possible to direct the initial interpretation towards an analysis of aspects of lithologic control on sediment physical properties.

Figure 5 shows the interpreted shear wave velocity structure for one location within the NRL gassy mud test-bed site. The profile represents the typical structure of the Eckernfoerde Bay mud. The interpretation confirms the expected low shear wave velocity at the surface (<10 m/s) for the soft muddy sediment and reveals the velocity gradient structure of the upper two to three metres. (Fig.4 is a plot of the travel time data for the same seismic record). These findings are in good agreement with those of other researchers working in the same area, notably Richardson (measurements with the ISSAMS) and Stoll (analysis of surface wave arrivals).

On analysing representative subsamples of the data collected for different lithologic environments along line 3, the seabed shear wave velocities for the sand and lag deposits were, as expected, consistently higher than any recorded within the muddy sediments at the NRL site, being typically in the range 40-50 m/sec at the surface, rising to 60-120m/s just below the surface. Looking slightly deeper within the sediment column, on numerous records there was evidence in the time-distance data of a more significant velocity discontinuity (a refracting surface) within the 2 to 5 metre depth range, the underlying material yielding velocities of the order of 200m/s. Similarly, velocity discontinuities could also be identified on some of the line 2 records and were taken as indicative of change in the physical property distribution. It now remains to ground-truth the geophysical interpretation through reference to various 'control' data sets (e.g. high resolution reflection data and sediment property data provided through core analysis).

Electrical resisitivity

The preliminary interpretation of electrical resistivity data indicates consistency with the surface sediment shear wave velocity variability. This was particularly apparent during recording over the spatially variable sediment of line 3. It seems likely therefore that a correlation exists between electrical resistivity and sediment property variability.

At this stage of the interpretation it has been possible to broadly classify the sediments on the basis of the measured values of electrical formation factor and to assign 'typical' values to the end members of the sediment grade scale: formation factors of approx. 1.5 for the fine sediments (muds) to 3.5 for the coarser materials (sands and gravels).

Sub-bottom profiling

Although after the survey it became apparent that the MDAS acquisition system had been intermittently malfunctioning, some single-channel and multi-channel data were acquired along the lines shown in fig.1. These data are currently being processed on the UCNW seismic workstation using the SierraSeis ISX software package and specialist 'geotechnical' software developed in-house within the University's Geophysics Laboratory. While the ultimate goal is the production of sectional displays of the physical property distribution along survey tracks, processing has so far been directed towards data enhancement

for seismic character recognition, and has concentrated on the investigation and analysis of 'anomalous' features within the zones of gas-charged sediment in Eckernfoerde Bay. With regard to the latter, perhaps the most interesting are the acoustic 'windows' which interupt the otherwise structurally featureless sections of acoustically-turbid gas-charged material. Figure 6 is one such feature which was noted on line 17 within the Mittelgrund. Some comments on this feature are included in the following discussion section.

DISCUSSION AND CONCLUSIONS

The 'magic carpet' geophysical sled measurements, which are effectively the result of remote sensing, have shown the Eckernfoerde mud to possess an extremely low shear wave velocity and to display a pronounced vertical velocity gradient within the depth zone sensed by the sled measurements i.e. the upper 2-3 metres. The velocity is as would be expected for a material of very low stiffness strength, while the measured gradient implies an increase in stiffness with depth. For sea floor sediments the latter is generally a direct result of the overburden effect. As reported by others (Briggs and Richardson 1994b), the shear wave velocity appears unaffected by the change in gas saturation a few tens of centimetres below the sediment surface (transition from fully water-saturated to gas-charged variable between approx. 30 and 100 cm - Fiedler and Stender 1994, Anderson et al. 1994, Abegg et al. 1994). The surface sediment's electrical formation factor is characteristically low, approaching the value for seawater i.e. unity, and is typical of a very high porosity mud (measured porosity values in core samples ranging from 84 to 91% - Briggs and Richardson 1994b).

In comparing the sled measured velocities for the gassy mud with those of others (Richardson and Griffin 1994, Stoll 1994), it is interesting to note that, despite the varying methods and scales of measurement, the shear wave velocity data are in good agreement over equivalent depth ranges. Relating these geophysical quantities to other physical property data for the gassy mud, probably the most significant correlation would be expected between shear wave velocity and shear strength. Briggs and Richardson (1994b) have already presented detailed shear strength and shear wave velocity profiles for the top 1 to 2 metres of sediment at one site in Eckernfoerde Bay. The measurements were made using piezoelectric bender bimorphs for shear waves and with a diver operated vane for shear strength. Both sets of data display a linear depth dependency (shear strength rising from 0.16kPa at the surface to 5kPa around 1.2 metres), lending support to the use of the shear wave velocity as a remote sensing tool in sea floor sediment analysis.

Concerning measurements in the other sedimentary environments, the sled data were as expected, sensitive to changes in seabed surface lithology which can be reasonably assumed to mirror changes in sediment physical properties. It is likely that more conclusive evidence of the geophysical/physical property relations will become apparent once the interpretation has been completed and the geophysical quantities ground-truthed through reference to control information. At this point the geophysical information will then be able to be used to make further inferences on the spatial distribution of sea floor sediment properties.

In terms of resolution of the 'magic carpet' system and its depth sensing capability, this is dictated both by the layout of the seismic array and by the structure of the sediment itself. The refraction methodology assumes an increase in velocity with depth hence the system is not able to sense a velocity inversion situation. With regard to resolution and application to studies of benthic boundary layer properties and processes, the system is probably best suited to rapid reconnaissance surveys and to the spatial mapping of sediment variability, with the finer detail being provided through stationary sampling with apparatuses such as NRL's ISSAMS.

Concerning the sled measured formation factors, it should be noted that these provide a bulk measure of the surface sediment pore space properties down to approximately 30-50 cm below the seabed surface. It should also be noted that, with regard to sensing the presence/effects of gas within the sediment pore space, the resolution is such that it would not be possible to differentiate between the two sediment states i.e. water-saturated and gas-saturated sediment, at the levels of gas concentration typically found in the Eckernforde Bay mud. Further, the small-scale variability in electrical properties noted by Briggs and Richardson (1994a) would not be expected to be apparent.

With regard to seismic sub-bottom profiling, this methodology has and will continue to make significant contributions to the understanding of process mechanisms operating in Eckernfoerde Bay. For example and in relation to fig.6, there are clearly processes operating within the Bay which 'create' the 'acoustic windows' seen in the boomer records. Based on the evidence of others (e.g. Whiticar & Werner 1981), it is perhaps not unreasonable to suggest that these 'windows' represent points at which groundwater is circulating upwards from the underlying Pleistocene sediments. Whiticar and Werner reported evidence of groundwater seeps in the sediments of Eckernforde Bay and attributed pockmark formation to the expulsion of freshwater. They also noted that pockmarks in the Bay often occurred directly above topographic highs in the underlying Pleistocene surface. Although lacking the 'supporting' evidence of a surface pockmark in the example boomer record presented in this report (processed amplitude envelope section), there does appear to be a significant change in seismic character of the surface sediments at the acoustic window location. It now remains to further analyse and supplement the digital data in an attempt to produce geotechnically-significant seismic attributes and ultimately, interpreted geotechnical property sections for all the area surveyed with the Uniboom.

REFERENCES

Abegg F, Anderson A, Butzi L, Lyons T and Orsi T (1994) Methane concentration and bubble characteristics in Eckernfoerde Bay. In: Proceedings of Gassy Mud Workshop, Report 14, Forschungsanstaslt der Bundeswehr fur Wasserschall-und Geophysik, Kiel, Germany

Anderson AL, Orsi TH and Lyons AP (1994) Measurement and description of upper seafloor sub-decimeter heterogeneity for macrostructure geoacoustic modeling. In: Richardson MD (Ed.), Coastal Benthic Boundary Layer Special Research

Program: Review of First Year. NRL Special Report NRL/MR/7431-94-7099: 14-43

Briggs KB and Richardson MD (1994a) High-frequency acoustic scattering from sediment surface roughness and sediment volume inhomogeneities. In: Richardson MD (Ed.), Coastal Benthic Boundary Layer Special Research Program: a Review of the First Year, NRL Special Report NRL/MR/7431-94-7099: 52-58

Briggs KB and Richardson MD (1994b) Geoacoustic and physical properties of near surface sediments in Eckernfoerde Bay. In: Proceedings of Gassy Mud Workshop, Report 14, Forschungsanstaslt der Bundeswehr fur Wasserschall-und Geophysik, Kiel, Germany

Davis AM Bennell JD, Huws DG and Thomas D (1989) Development of a seafloor geophysical sledge. Marine Geotechnology 8: 99-109

Davis AM, Huws DG and Bennell JD (1991) Sea floor shear wave velocity data acquisition: procedures and pitfalls. In: JM Hovem et al. (Eds.), Shear Waves in Marine Sediments, Kluwer Academic Publishers, Dordrecht, The Netherlands: 329-336

Fiedler H and Stender I (1994) The absorption layer in the Eckernfoerde Bay. In: Proceedings of Gassy Mud Workshop, Report 14, Forschungsanstaslt der Bundeswehr fur Wasserschall-und Geophysik, Kiel, Germany

Haynes R, Davis AM, Reynolds JM and Taylor DI (1993) The extraction of geotechnical data from high-resolution seismic reflection data. In: Offshore Site Investigation and Foundation Behaviour, Society for Underwater Technology, Kluwer Academic Press 28: 215-228

Huws DG, Davis AM and Bennell JD (1991) Mapping of the seabed via in situ shear wave (SH) velocities. In: JM Hovem et al. (Eds.), Shear Waves in Marine Sediments, Kluwer Academic Publishers, Dordrecht, The Netherlands: 337-343

Richardson MD and Griffin SR (1994) In situ sediment geoacoustic properties. In: Richardson MD (Ed.), Coastal Benthic Boundary Layer Special Research Program: a Review of the First Year. NRL Special Report NRL/MR/7431-94-7099: 146-148

Seibold E, Exon N, Hartmann M, Kogler FC, Krumm H, Lutze GF, Newton RS and Werner F (1971) Marine Geology of Kiel Bight. In: Muller G (Ed.), Sedimentology of parts of Central Europe, Guidebook, 8th International Sedimentology Congress, Heidelberg: 209-235

Stoll RD (1994) Experimental and theoretical studies of near-bottom sediments to determine geoacoustic and geotechnical properties. In: Richardson MD (Ed.), Coastal Benthic Boundary Layer Special Research Program: a Review of the First Year. NRL Special Report NRL/MR/7431-94-7099: 275-293

Whiticar MJ and Werner F (1981) Pockmarks: Submarine vents of natural gas or freshwater seeps? Geo-Marine Letters 1: 193-199

PUBLICATIONS/PRESENTATIONS ARISING FROM UCNW'S INVOLVEMENT IN THE CBBLSRP:

Davis AM, Haynes R and Huws DG (1994) Geophysical approaches to determining the geotechnical characteristics of sea floor sediments: Acquisition and analysis of shear wave, electrical resistivity, and digital seismic sub-bottom profiler data. In: Proceedings of Gassy Mud Workshop, Report 14, Forschungsanstaslt der Bundeswehr fur Wasserschall-und Geophysik, Kiel, Germany

Davis A, Huws D and Haynes R (1995) Geophysical Ground-truthing Experiments in Eckernfoerde Bay. Submitted for inclusion in a Special Issue of Geo-Marine Letters. Abstract submitted to 128th Meeting of Acoustical Society of America.

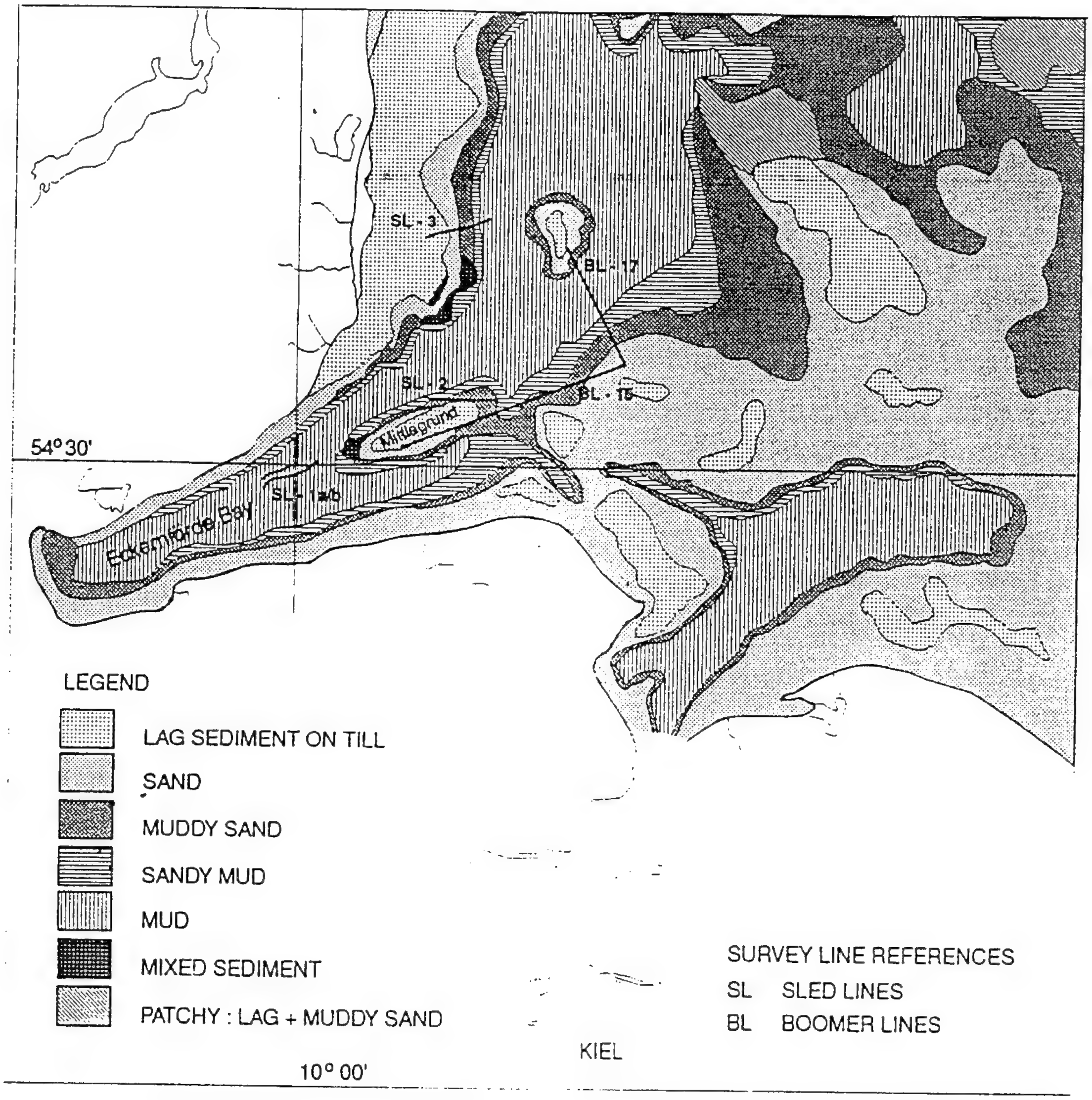


Fig.1 Location map showing UCNW's sled and Uniboom survey tracks in relation to sediment distribution

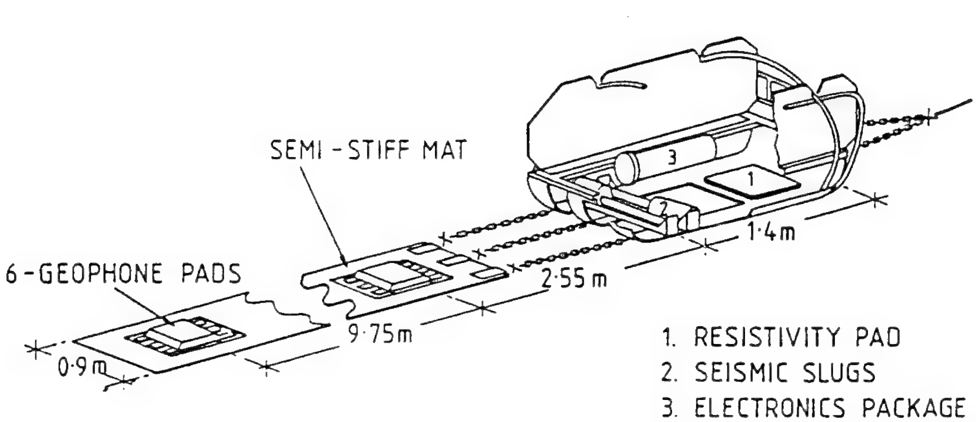


Fig.2 The UCNW sea floor sled- 'magic carpet'

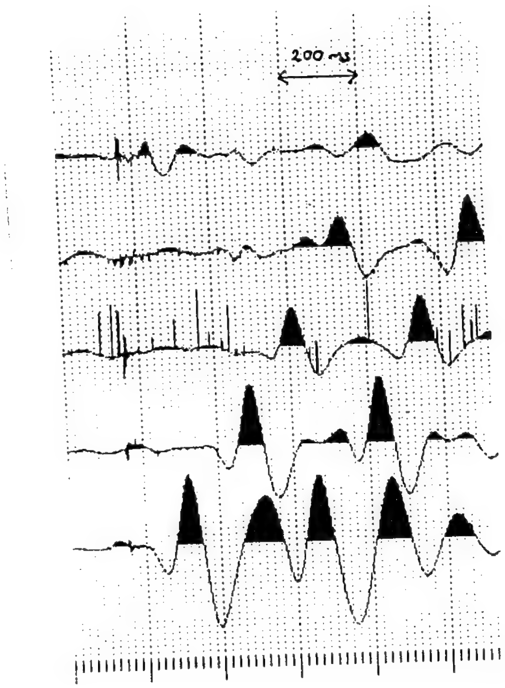


Fig.3 Example shear wave record collected with the sled operating over the soft muds at the NRL test site

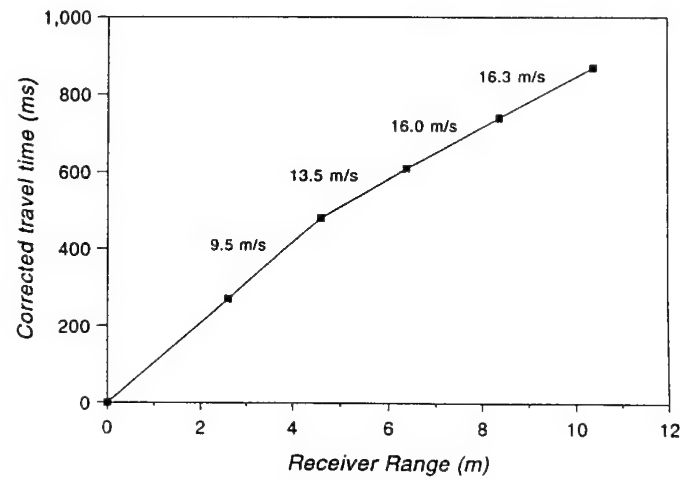


Fig.4 A typical shear wave travel-time plot for data collected over the NRL site

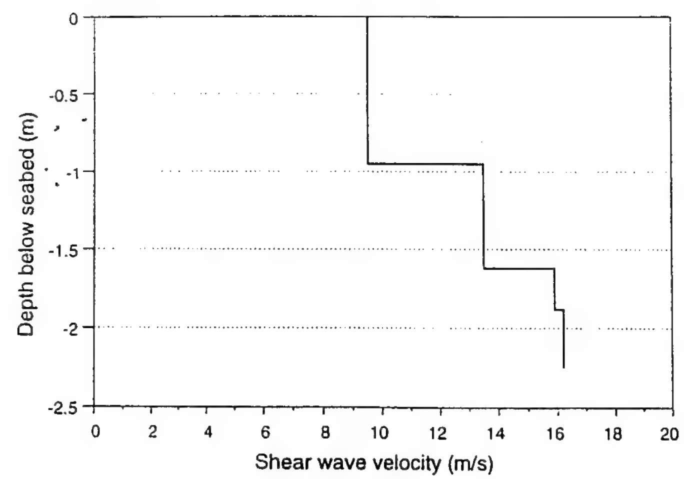


Fig.5 Interpreted velocity depth profile for the soft mud at the NRL test site

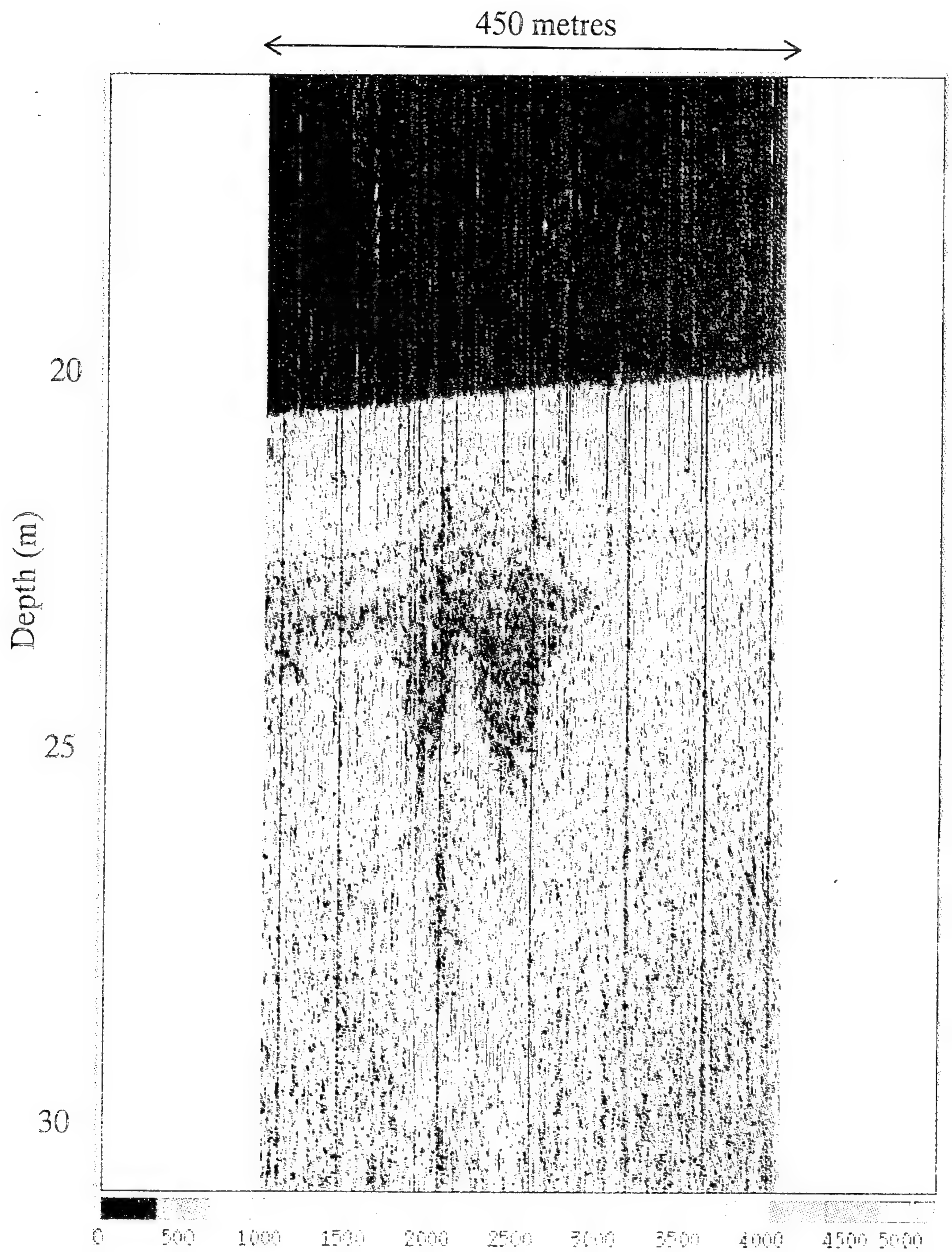


Fig.6 Instantaneous amplitude plot for a part of line 17 showing an 'acoustic window' in an area of predominantly gassy sediment. The gas-charged sediments appear as medium to high amplitude zones of acoustic 'turbidity' while the glacial till surface appears as a high amplitude coherent reflector (at depths of 24-27m).

2.7 Analysis of the Rheological Properties of Nearbed (Fluid Mud) Suspensions Occurring in Coastal Environments (Principal Investigators: R. W. Faas)

Yearly Report to the Naval Research Laboratory

Submitted by:
Richard W. Faas

Department of Geology
Lafayette College
Easton, PA 18042

PROGRESS DURING 1994

1. Six (6) interface samples were collected by the Nittrouer/Lopez team during the June/July Eckernfoerde Bay cruise. These samples were transfered to the sedimentology laboratory at the Royal Belgian Institute for Natural Sciences, Brussels (KBIN) where they were analyzed for their particle size distribution, organic matter and carbonate content. Table 1 reports these data.

2. Plans were developed and construction begun for a settling tube which will be used to perform hindered settling experiments of fluid muds from different fine-sediment environments, including the Eckernfoerde Bay. The settling tube is 2 m long and 10 cm wide (ID). It is being designed to fit into the core logger at Texas A&M University where experiments had been planned for October-November 1994. The tube is being fitted with 6 differential pressure transducers (Figure 1) and will measure and record the changing pore pressures generated by suspensions which settle due to gravitational compaction during a simulated tidal slack water interval. The core logger is equipped with a gamma ray density sensor and a compressional wave velocimeter which will follow the descending lutocline (sediment-water interface) and will measure density and sound velocity as they change with time and pore pressure dissipation. I am also installing a base to the unit which will allow me to introduce gas into the system. It should be possible to control the bubble diameters and abundance while gamma density and compressional wave velocity measurements are made during the self-weight consolidation of the material. The basic equipment has been constructed and only awaits installation of the transducers.

Completion of this experimental phase hinged upon the availability of the TAMU core logger. However, the core logger has been detained aboard a Russian oceanographic vessel and its arrival date back to TAMU is uncertain.

3. During September 1994 I prepared a paper for submission to Geo-Marine Letters (deadline October 1, 1994). I have also been performing rheological analyses on a group of fine-grained sediments from St. Louis Bay, MS (northern half of the bay is clay-rich), and on a set of aragonite muds that I collected a number of years ago from Florida Bay. These should provide a baseline for the shear stress - rate of strain behavior of carbonate muds and a guide to resus- pension prediction of fine-grained carbonate material.

Richard W. Faas
Professor of Geology

Encl: Table 1 - Textural Properties of Eckernfoerde Muds
Figure 1 - Diagram of Settling Column

TABLE 1 - TEXTURAL PROPERTIES OF ECKERNFOERDE MUDS

SAMPLE	SAND	SILT	CLAY	S/C	MEAN DIA.	OM	CaCO3
#	%	%	%		(mm)	%	%
BC 223	3.63	40.73	55.84	0.74	0.71	18.32	0.3
BC 225	4.33	52.21	43.46	1.20	1.20	18.03	0.5
BC 232	2.35	51.85	45.80	1.13	1.88	***	***
BC 237	3.82	44.37	51.31	0.86	2.24	***	***
BC 238	2.75	41.55	55.70	0.75	0.68	20.03	1.1
BC 249	3.78	43.95	52.27	0.84	2.25	***	***
BC 250	22.43	32.51	45.06	0.72	2.17	13.92	0.2
BC 251	1.42	45.47	53.11	0.86	0.68	10.72	0.2
BC 253	3.28	43.92	52.80	0.83	0.74	18.32	***
BC 257	2.67	43.39	53.94	0.80	1.92	18.47	***
BC 264	1.03	41.61	57.36	0.73	0.64	18.04	1.2
Site H	11.41	48.71	39.88	1.22	2.12	15.01	7.5

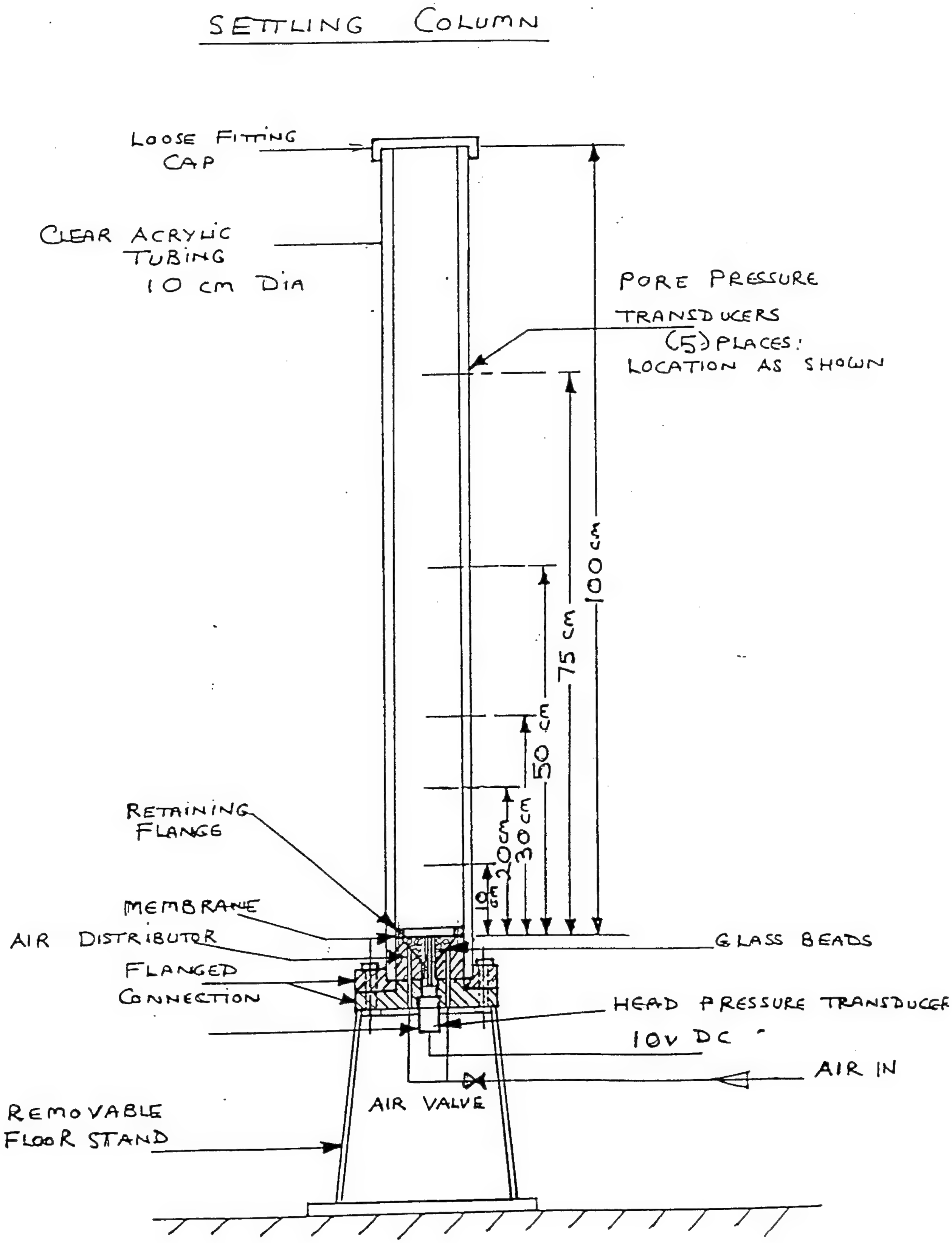

SETTLING COLUMN
LOOSE FITTING CAP
CLEAR ACRYLIC TUBING 10 cm DIA
PORE PRESSURE TRANSDUCERS (5) PLACES: LOCATION AS SHOWN
100 cm
75 cm
50 cm
30 cm
20 cm
10 cm
RETAINING FLANGE
MEMBRANE
AIR DISTRIBUTOR
GLASS BEADS
FLANGED CONNECTION
HEAD PRESSURE TRANSDUCER
10V DC
AIR IN
AIR VALVE
REMOVABLE FLOOR STAND

Figure 1.

2.8 Measurement of High-Frequency Acoustic Scattering From Coastal Sediments (Principal Investigators: D.R. Jackson and K.L. Williams)

CBBLSRP FY94 YEAR-END REPORT

Darrell R. Jackson
Kevin L. Williams
Applied Physics Laboratory, College of Ocean and Fishery Sciences,
University of Washington, Seattle, Washington 98105

General Summary of Work During This Period

The primary activities in FY94 were analysis and interpretation of data from the FY93 measurements in Eckernfoerde Bay and at Panama City and upgrade of the Benthic Acoustic Measurement System (BAMS). Measurements at both locations included long-term bottom backscattering observations using BAMS (operating at 40 kHz) and shorter-term bottom bistatic scattering measurements using a mobile receiving array with BAMS serving as the acoustic source. The backscatter data were analyzed using a correlation method which measures the spatial and temporal dependence of benthic change. The rate of decorrelation was two orders of magnitude more rapid at a sandy site near Panama City site than at a silty site in Eckernfoerde Bay, Germany, and both sites were characterized by "hot spots" or localized regions of activity. Bistatic scattering data were reduced to scattering strength estimates and compared with a model that incorporates interface and sediment volume scattering. The model and data are consistent for the Panama City site, but not for the Eckernfoerde site. This is to be expected since the model does not treat bubble scattering.

Backscattering Correlations

Complex correlations were computed between separate scans in order to study the spatial and temporal scales of benthic change (Dworski and Jackson, 1994). Figure 1 shows two correlation images from the Eckernfoerde Bay data set. The diameter of these images is 100 m, and true North is vertical (upward). The second scan was used as a reference, and correlation comparisons were made with scan numbers 100 (98 hours lag) and 250 (248 hours lag). High correlations near unity (shown in blue) correspond to regions of low activity, while lower correlations (shown in warmer colors) correspond to regions of higher activity, or greater change. The "Lambert parameter" images shown in Fig. 1 will be discussed in the following section. The correlation images reveal a spatial pattern of change that is patchy, with low correlation of order 0.7 in small regions whose scale is of the same order or slightly larger than the image resolution (about 5 m). Comparison of the two correlation images shows that, in the 150-hour interval between scans 100 and 250, considerable change occurred in the azimuthal sector from Southwest to North. In opposition to this sector of activity, there is a large sector of low activity.

The correlation images from the Panama City site (Fig. 2) are markedly different than those from the Eckernfoerde Bay site. The same scale and compass alignment apply to these images, but the reference scan was chosen as number 1057, late in the deployment. The lags of the scans used for comparison are very small, one hour and 3.333 hours. Though these lags are smaller by an approximate factor of 100 than those used in the Eckernfoerde Bay images, the decorrelation levels are greater. Thus, the rate of change of the bottom at this site, in an acoustic sense, is greater than that at the Eckernfoerde Bay site by a factor of order 100. The Panama City images are patchy, with "hot spots" of low correlation that are smaller than or comparable in size to the 5 m resolution. The elongated "hot" region in the second image, to the east of center, was the result of alteration of the bottom by NRL divers, who drug a heavy chain over this region.

Lambert Parameter

The Lambert parameter images resemble conventional sonar images, since this parameter is an indicator of acoustic "brightness" of the sea floor. Figure 1 shows two images of the Lambert parameter at the Eckernfoerde site corresponding to the scans used in making the corresponding correlation images. Based on the work of Tang, et al. (1994), it can be assumed that these images are due to scattering by a submerged methane layer. We interpret these images as representing gas concentration rather than layer depth. This interpretation was reached by employing the interferometric bathymetry capability of BAMS which revealed a very small correlation between scatterer strength and depth. It is interesting that the greatest gas concentration is in the eastern sector while the region of greatest change is in the western sector.

Figure 2 shows two Lambert parameter images from the Panama City site juxtaposed with corresponding correlation images. Both the Lambert and correlation images are patchy, but "bright" spots in the Lambert images do not necessarily correspond to "hot" spots in the correlation images. In fact, a very bright spot appearing to the South at mid range in the Lambert images falls within a region of high correlation, or low activity. The very bright spot ENE of center in the Lambert images is an acoustic target used as a reference marker. It is invisible in the correlation images as it produced a strong, repeatable echo. The bottom-modification experiment produced very little change in the Lambert image, neither increasing or decreasing the acoustic brightness. From this, and the large decorrelation seen in Fig. 2, it can be concluded that the experiment rearranged the scatterers substantially without changing their strength. This may indicate that the scatterers are truly surficial, residing in the layer affected by the chain, or it may indicate that alteration of fine-scale topography altered the appearance of deeper-lying scatterers which are viewed through the randomly rough, refractive interface.

Time Series

A major CBBL issue is environmental forcing of the acoustic properties of the sea floor. We have derived time series for several acoustically derived variables in order to facilitate comparison with oceanographic time series from the same experiment, especially the data of Friedrichs and Wright (1994) from the Eckernfoerde early deployment. Figure 3 shows four acoustically derived time series; each will be discussed in turn.

Six-Hour-Lag Correlation, Eckernfoerde

This is the magnitude of a complex cross-correlation of the echo time series with a lag of six hours. The correlation is formed for short pieces of the echo time series at times corresponding to the ranges indicated on the plot. Prominent events are seen at days 5.5, 9, and 12.5. The fixed-lag correlation shows immediate change, at least on a time scale of six hours, but this change may be transient and not permanent. That is, fish or suspended material may float by the sonar and cause a change and decorrelation, but there would be a recorrelation as soon as these scatterers move away.

Running-Lag Correlation, Eckernfoerde

In this case, an early scan is used as a reference and compared with all subsequent scans. This running-lag correlation highlights permanent, irreversible change that might not be evident in the fixed-lag correlation. Transient events are identifiable as spikes in which the correlation first drops and then rises. This behavior is seen in the three events, but one also sees that these events caused some permanent decorrelation. That is, the correlation drops and rises, but does not rise to

its former level. There is a definite "descending staircase" appearance to the correlation vs. lag with the downward steps being the events of interest.

Apparent Sound Speed Change, Eckernfoerde

This is an acoustically derived time series for change in sound speed (Jackson and Dworski, 1992), averaged over the interval between the sonar transducer (5.1 m above the sea bed) and the scatterers (gas bubbles 1.2 m below the sea bed). Unfortunately, the APL CTD malfunctioned on this deployment, so no sound speed time series is available for comparison. The VIMS temperature series shows fluctuations of order 0.1°C, which would account for only 0.4 m/s of the observed sound speed variation. Salinity fluctuations of 1 ppt could account for the remainder.

Apparent Scatterer Altitude Above Bottom, Eckernfoerde

This series is obtained by measuring the vertical angle of the incoming acoustic energy using an interferometric technique (Tang, et al. 1994). This calculation neglects refraction due to vertical stratification of the water column and sediment. Most of this time series is flat and indicates that scattering is coming from the gas layer, about 120 cm below the interface. (Altitude is defined as positive for points above the interface, negative for points below.) The bumps at days 9 and 12 may represent a refractive effect rather than real upward motion of the gas layer. This is indicated by the range dependence of the effect, which is approximately quadratic. An effect of this magnitude could be caused by a 1.0° temperature gradient or a 3.5 ppt salinity gradient in the 5.1 m interval defined by the tower height. Note that the first decorrelation event (at day 5.5) is not accompanied by a bump in the altitude series, so there was apparently no strong stratification near the bottom in this case.

The correlation events at days 9 and 12 correspond roughly to the two peaks in the VIMS OBS data and line up almost perfectly with the two major peaks in the bottom stress (Friedrichs and Wright, 1994, Fig. 12). The three correlation events line up reasonably well with episodes of into-bay flow as measured by the VIMS tetrapod. These similarities are suggestive, but it is not clear how any of these oceanographic fluctuations could induce changes in the bubble layer

<u>Bistatic Scattering</u>

A simplified picture of the bistatic measurement technique is shown in Fig. 4. The primary consideration in the experiment design was coverage of the three angular variables defined in the figure. This dictated use of a mobile receiving array in order to obtain statistically significant numbers of bistatic scattering measurements in any region of bistatic angle space. The total data set for each site is broken into separate files, with each file consisting of data taken with the mobile array during a 360° rotation of the tripod transmitter array. This rotation comprises 72 positions (5° increments) at each of which the 40 kHz signal is emitted. As shown in Fig. 4 the mobile array is steered so that the center of the transmit and receive beams intersect each other on the bottom such as to realize different bistatic scattering angles. Measurement of all the geometrical parameters needed to determine the bistatic angles requires a several supplemental devices including compasses, ranging transducers, and inclinometers.

The first stage of the analysis effort concerned the determination of these angles from the data set. In the second stage, a simulation code was used to generate synthetic intensity time series including the experimental geometry, the transmitted pulse length, and the beam patterns of the receiving and transmitting arrays. The simulations employed the bistatic scattering model with preliminary values for the input parameters. These simulations allowed an assessment of the angular

resolution and the deleterious effects of sidelobes and surface scattering (Williams and Jackson, 1994). Once "good" portions of data had been thus identified, these synthetic time series were compared with field data to estimate bistatic scattering strength, which was determined by correcting the model scattering strength by the difference in dB between the measured and simulated intensity time series.

Measured scattering strengths are compared with a bistatic scattering model (Jackson 1994) in Figs. 5 (Eckernfoerde) and Fig. 6 (Panama City). The model curves are tentative, as measured values are presently available for only a few of the model input parameters (density ratio, sound speed ratio, and attenuation, measured by Briggs and Richardson of NRL). The model also requires interface roughness parameters and sediment inhomogeneity parameters. These should be available in the near future, but, for the present, estimates based on historical data from other sites were used.

In presenting data dependent upon three variables, a compromise will be made to simplify the interpretation. The data have been lumped into rather broad bins in grazing angle and then displayed as functions of the azimuthal angle. The bin intervals for the incident (thetai) and scattered (thetas) grazing angles are indicated in Figs. 5 and 6. The model curves are calculated for the extremes (smallest and largest thetai, thetas). This technique eliminates data where the incident and scattering angles are not about the same but does allow a simpler view of the data/model comparison. The backscatter data obtained from the tower receiver are included and appear at the extreme right of each figure (phi = 180°).

The model/data comparison for the Eckernfoerde site is questionable, as the model treats sediment volume scattering as due to weak, continuous inhomogeneity (Lyons, et al., 1994) rather than by gas bubbles. In this case, the inhomogeneity parameters were estimated based on backscattering strengths from silty sites with no gas content. An initial examination reveals that, while the model is not in obvious conflict with the overall behavior of the data, the data show lower scattering strengths than the model in the azimuthal range 50–75°. This behavior may be a signature of bubble scattering; at any rate, these data should prove useful in checking bubble scattering models.

The Panama City model/data comparisons (Fig. 6), though tentative, appear more successful. The model predicts a plateau with scattering strength roughly independent of azimuth for directions away from the forward direction (phi = 0). The level of this plateau is predicted to increase with increasing grazing angles (both thetai and thetas). This behavior is seen in the data (compare the top two panels of Fig. 6), although the data show considerable scatter below the plateau in the 10–20° interval. Finally, the predicted increase in scattering strength as azimuthal angle approaches the forward direction is suggested by data displayed in the lower two panels, although the quantity of data is too small to be definitive.

BAMS Upgrade

The Benthic Acoustic Measurement System is being upgraded to operate at two frequencies, 40 kHz (the old frequency) and 300 kHz. This upgrade is to be completed in time for the Key West experiment and allows arbitrary schedules for scans at the two frequencies, where the old system required a fixed time interval between scans. The 300 kHz subsystem will have substantially better resolution than the 40 kHz subsystem. Angular resolution is 5° and 1°, respectively at 40 and 300 kHz. Signal bandwidth is 2 kHz and 10 kHz respectively. Thus, the 300 kHz system will have a fivefold improvement in both angular and range resolution. Like the 40 kHz subsystem, the 300 kHz subsystem will have interferometric bathymetry capability.

References

Dworski, J.G. and Jackson, D.R. (1994), "Spatial and temporal variation of acoustic backscatter in the STRESS experiment," Continental Shelf Research **14**, 1221–1237.

Jackson, D.R. and Dworski, J.G. (1992), "An acoustic backscatter thermometer for remotely mapping seafloor water temperature," J. Geophysical Research **97**, 761–767.

Friedrichs, C.T. and Wright, L.D. (1994), "Resonant internal waves and their role in transport and accumulation of fine sediment in Eckernfoerde Bay, Baltic Sea," Continental Shelf Research (submitted).

Jackson, D.R (1994), "Models for scattering from the sea bed," Proceedings of International Conference on Underwater Acoustic Scattering, Weymouth, UK.

Lyons, A.P., Anderson, A.L. and Dwan, F.S. (1994), "Acoustic scattering from the seafloor: modeling and data comparison," J. Acoust. Soc. Am. **95**, 2441–2451.

Publications and Presentations

Jackson, D.R. and Williams, K.L. (1994), "Acoustic observations of benthic variability," 1994 Ocean Sciences Meeting, Eos, Transactions, **75**, 181.

Tang, D., Jin, G, Jackson, D.R., and Williams, K.L. (1994), "Analyses of high-frequency bottom and sub-bottom backscattering for two distinct shallow water sites," J. Acoust. Soc. Am. **96**, 2930-2936.

Williams, K.L., Dahl, P.H., and Jackson, D.R. (1994), "Some current efforts and future plans in surface and bottom scattering characterization," Proceedings of The Technical Cooperation Program, Subgroup G, Symposium, Heriot-Watt University, Edinburgh, UK, 267–276.

Williams, K.L. and Jackson, D.R. (1994), "Monostatic and bistatic bottom scattering: Recent experiments and modeling," Proceedings OCEANS `94.

Fig. 1 Correlation and Lambert parameter images from the Eckernfoerde Bay site.

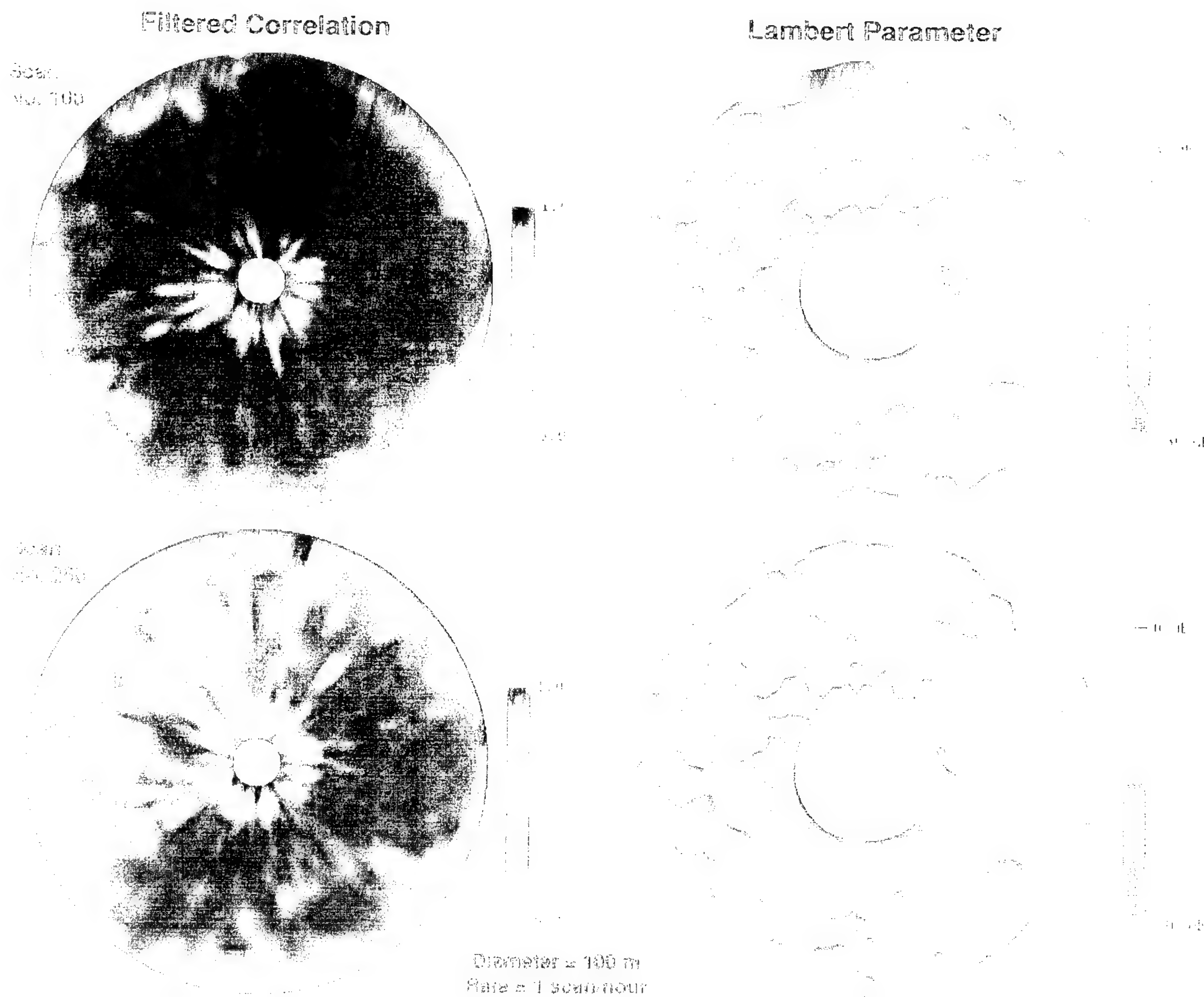
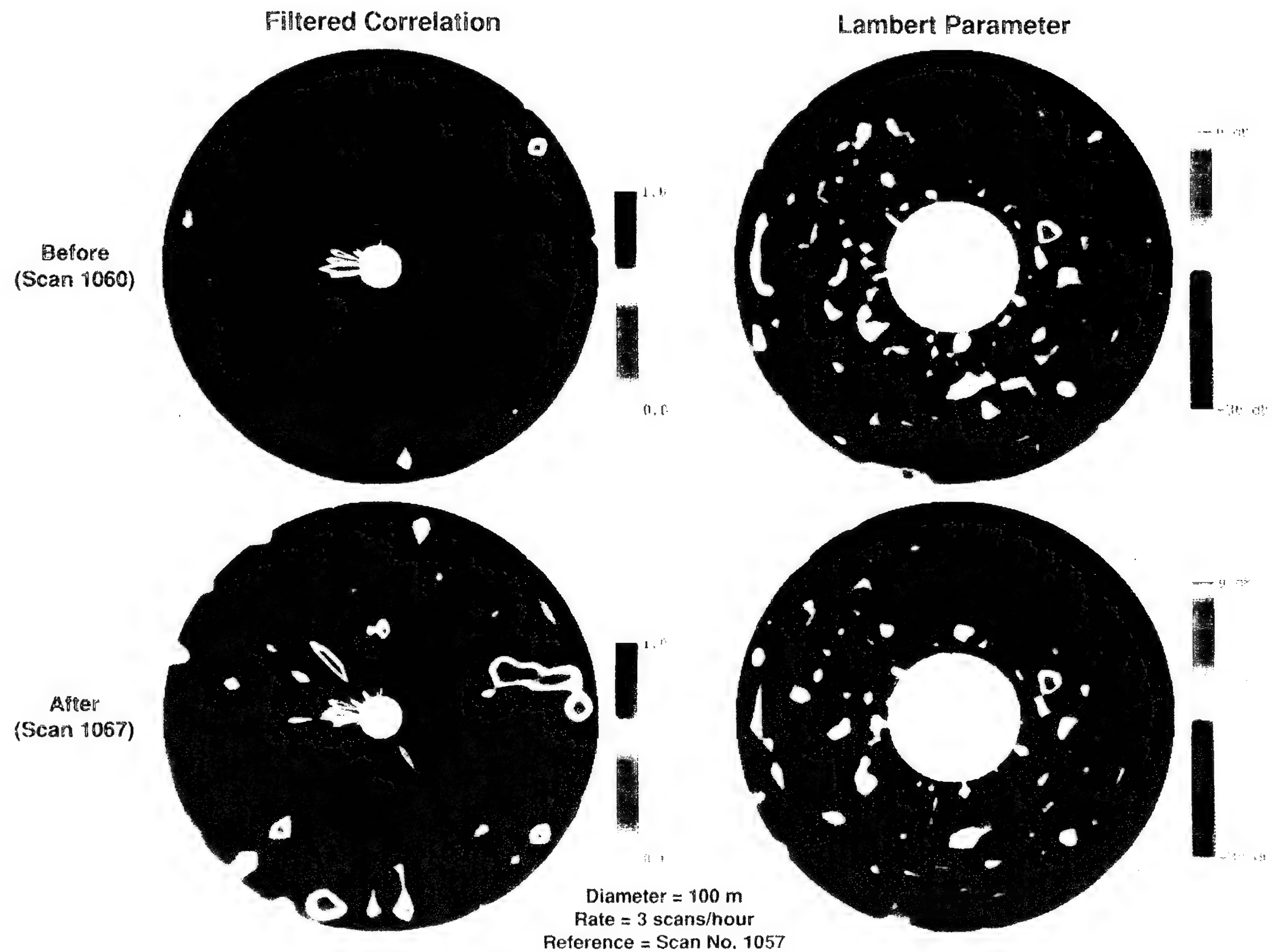


Fig. 2 Correlation and Lambert parameter images from the Panama City site.



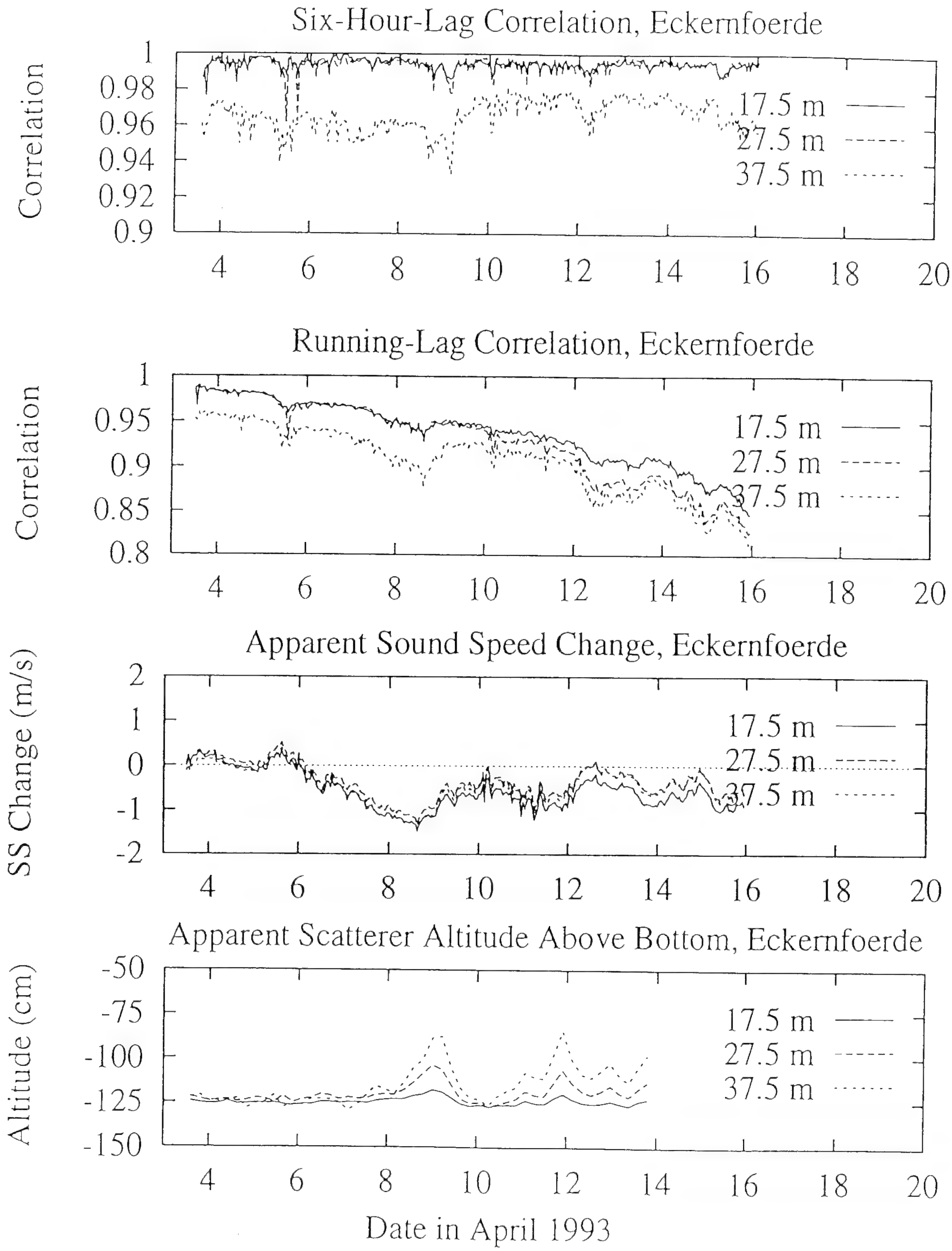


Fig. 3 Acoustically derived time series from the Eckernfoerde early deployment.

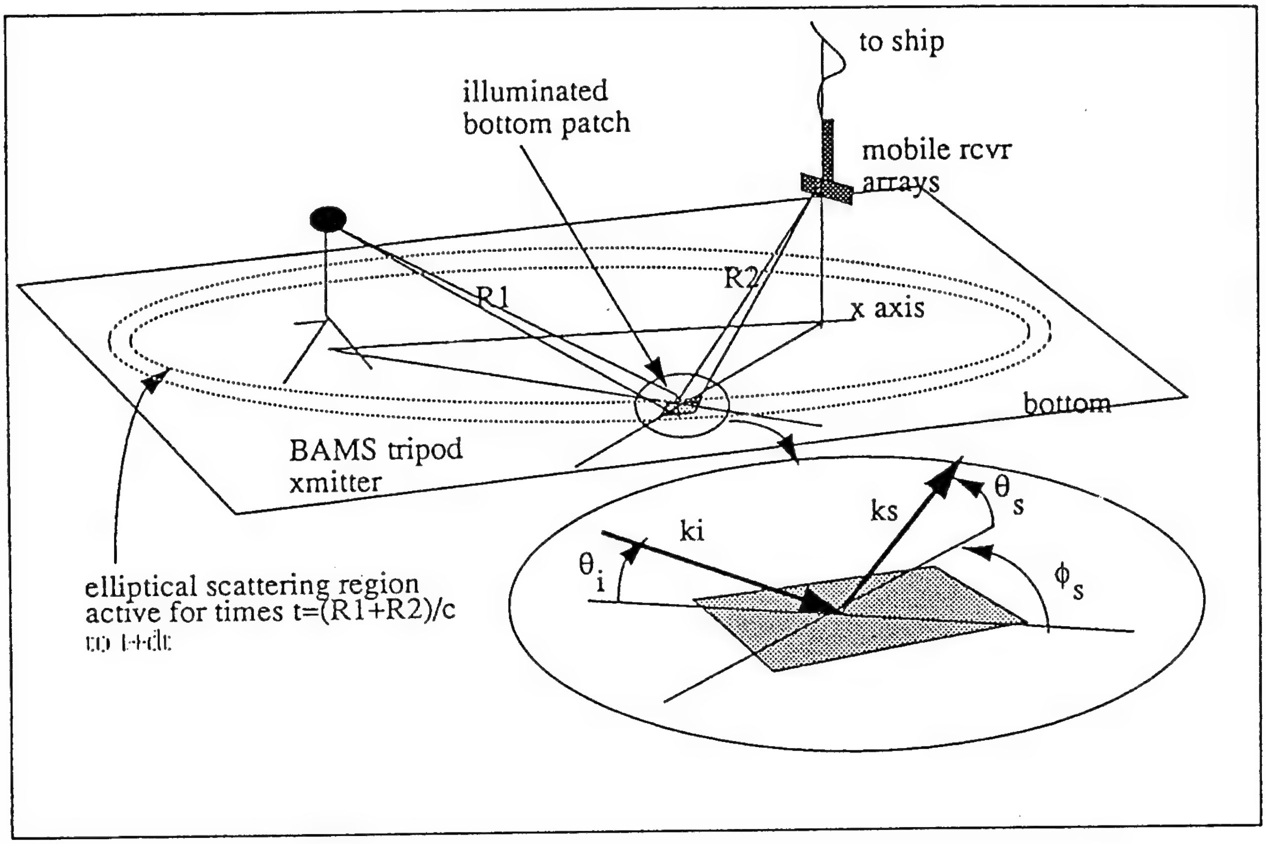


Fig. 4 Bistatic geometry and definitions of variables.

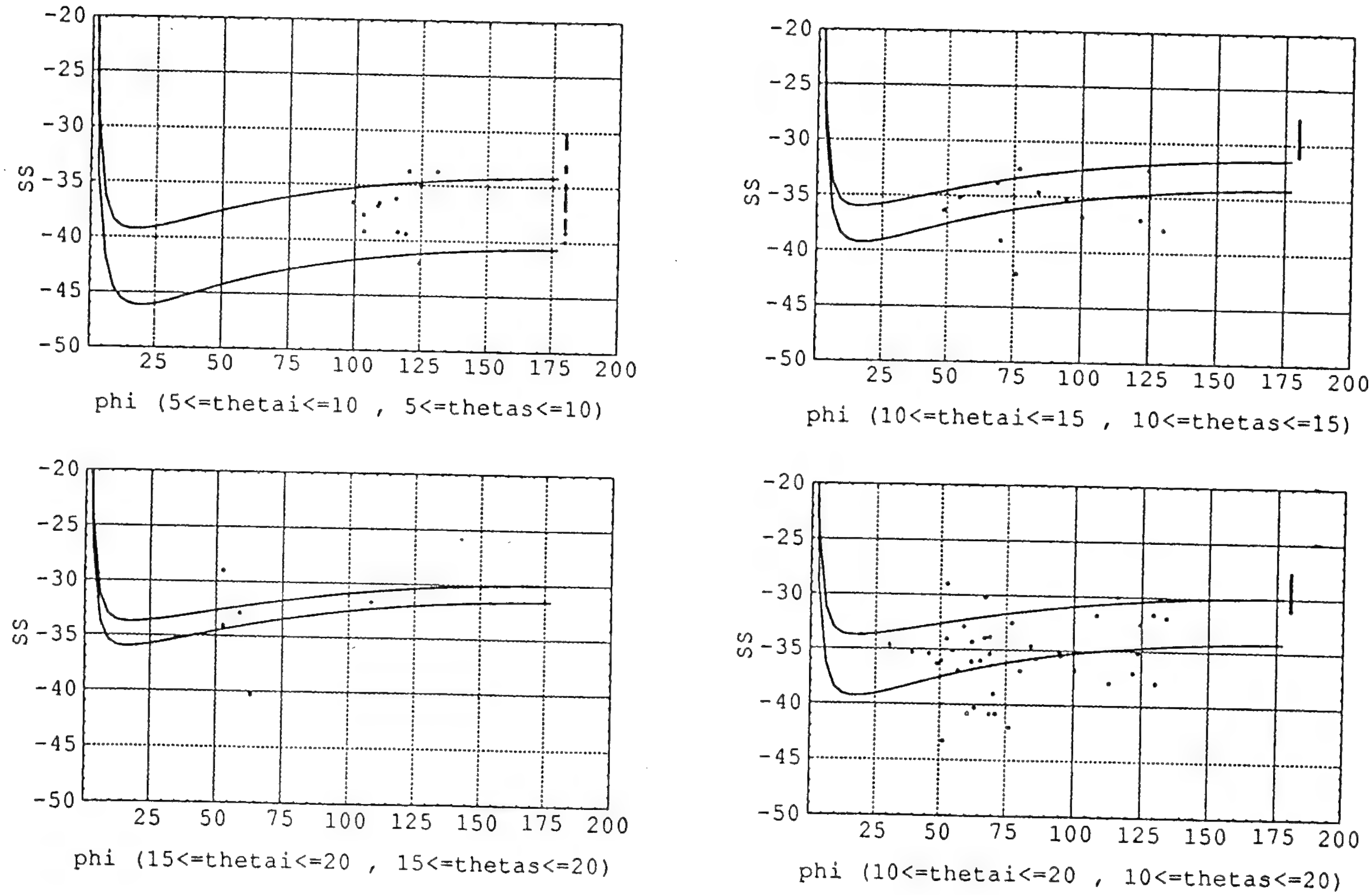


Fig. 5 Model/data comparisons for bistatic scattering at the Eckernfoerde site.

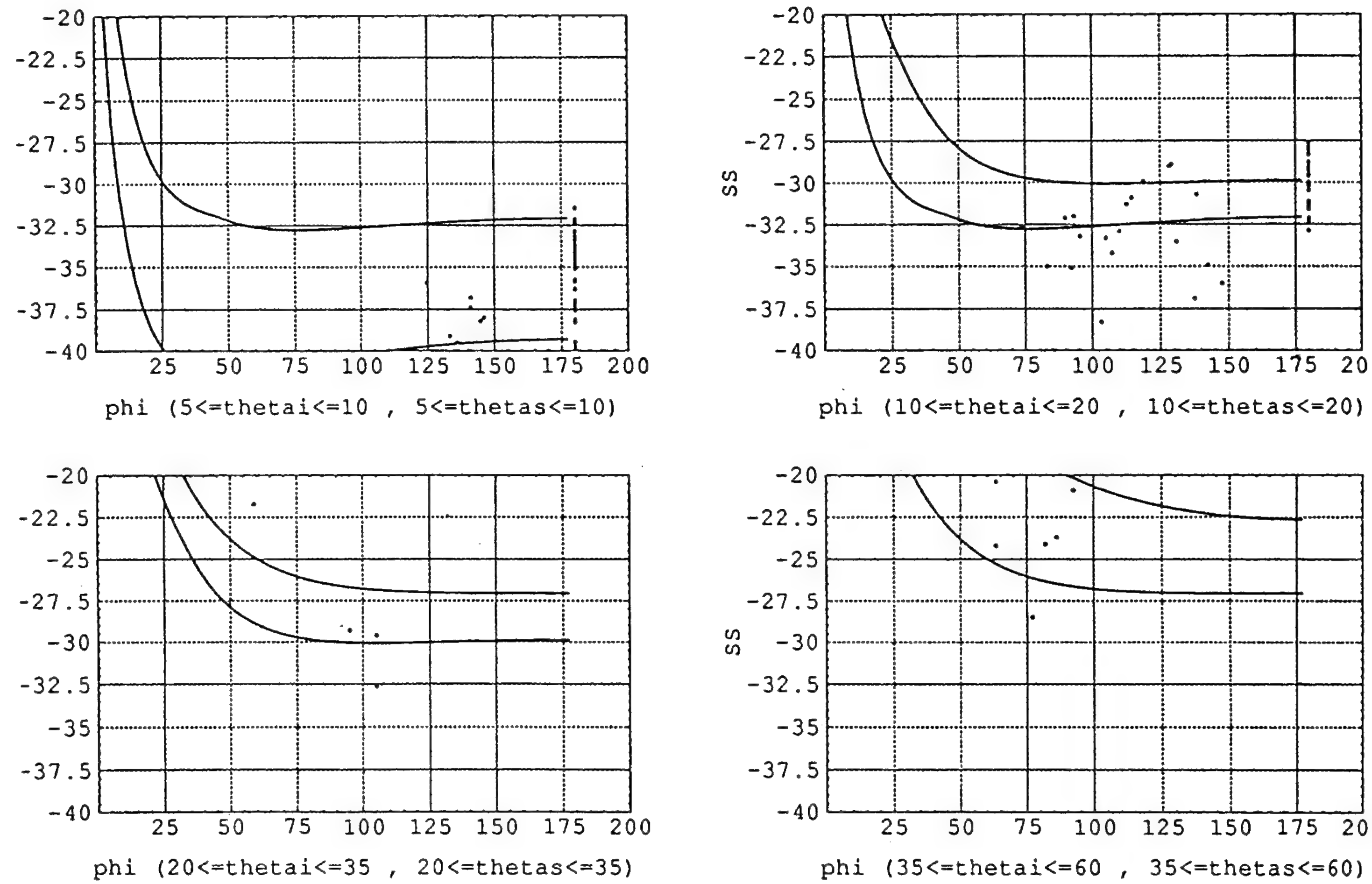


Fig. 6 Model/data comparisons for bistatic scattering at the Panama City site.

2.9 Structural Analysis of Marine Sediment Microfabric (Principal Investigators: J.J. Kolle and A.C. Mueller)

STRUCTURAL ANALYSIS OF MARINE SEDIMENT MICROFABRIC CBBLSRP FY94 YEAR-END REPORT

Jack J. Kolle, Alan C. Mueller

QUEST Integrated Inc., 21414 68th Ave S., Kent, WA 98032

and Jack Dvorkin

Dept. of Geophysics, Stanford University, Stanford, CA 94305-2215

INTRODUCTION

The Coastal Benthic Boundary Layer Special Research Project (CBBLSRP) represents a comprehensive study of geoacoustic and geotechnical properties in a variety of shallow marine environments. The first two field studies carried out under this program included a shallow muddy bottom in Eckernfoerde Bay near Kiel, Germany, and the West Florida sand sheet near Panama City, Florida. The studies included sampling of the bottom to determine the sediment structure on a microscopic scale; and in-situ measurements of compression and shear wave velocity. An important component of this project is an attempt to link sediment microfabric with acoustic and geotechnical properties(Richardson 1994)

Modeling of elastic wave propagation in sediments has resulted in a wide variety of theories based on idealized mathematical descriptions. Wang and Nur (1992) list 14 theories of wave propagation which may be divided into 4 classes; effective medium models, wave propagation models, inclusion theories and contact theories. Effective medium models assume that the bulk elastic properties can be obtained through some average the properties of component moduli. The simplest example is Wood's equation which assumes that the bulk modulus of a fluid containing gas bubbles is the volume-weighted average of the fluid and gas moduli. Wave propagation theories provide elastic moduli based on the moduli of the solid phase, the solid framework and the fluid. These are represented by Gassmann's equation for static moduli and Biot theory for dynamic moduli. Inclusion and contact models provide framework moduli based on explicit descriptions of the sediment geometry. Examples include the Kuster-Toksoz (1974) and Berryman (1974) self-consistent models for dilute distributions of inclusions in a solid matrix. These models have found limited application since ellipsoidal inclusions are rarely found in nature. Contact models have evolved from evaluations of the moduli of regular packings of spheres to random packings, cementation effects, hydrodynamic effects at contacts and stress induced anisotropy (Stoll 1989). All of these efforts have focused on the limited problem of predicting velocities and dispersion in clean, well-sorted silt and sand.

The CBBL program includes studies of a variety of bottom sediment environments which are not amenable to the explicit contact and inclusion theories described above. Our objective is to develop a uniform technique which is capable of determining geoacoustic properties of sediments from microfabric observations. We have applied a microstructure analysis technique (MISTRA) to obtain saturated and

dry framework moduli of any sediment microfabric. MISTRA uses the finite element technique to carry out an analysis of a structural grid consisting of solid, water and gas phases (Mueller and Kolle 1991). Periodic, generalized plane strain boundary conditions appropriate for a representative unit cell embedded in an infinite medium are applied to a microstructure grid obtained from image analysis or using statistical structure generation routines. The properties of water or gas are parameterized with elastic moduli chosen to match the compressibility of water and very low shear modulus to calculate saturated and dry framework elastic moduli. These moduli can then be used to obtain low-frequency acoustic wave velocities and Biot dispersion in multi-phase materials. The power of this approach lies in the ability to deal with a broad range of sediment structures.

Objectives

Our objective in FY94 was to evaluate the predictive capability of the MISTRA analysis procedure by generating poroelastic constants for representative marine sediments and predict attenuation, dispersion and permeability relationships. In particular, we planned to model three sediment types studied in the first year of the CBBL program.

1. Compact sand in the West Florida sand sheet
2. High porosity clay sediment in Eckernfoerde Bay
3. Gassy clay sediment in Eckernfoerde Bay

COMPACT SAND

Although a CBBL field experiment was carried out on the West Florida sand sheet in 1993, no data on the sediment microstructure or in-situ acoustic velocities was available in FY94. We therefore used a stochastic procedure to generate models of sand and compared this data with laboratory studies of acoustic velocity in sand. In this analysis we wanted to determine the limitations of an existing MISTRA code which uses structured finite element analysis grids. Figure 1 shows two structured, 20x20 stochastic sand grids with 22% and 39% porosity. These grids are generated by placing circular sand grains at a series of randomly selected points until the desired porosity is reached. The algorithm also allows for random variability in the grain diameter.

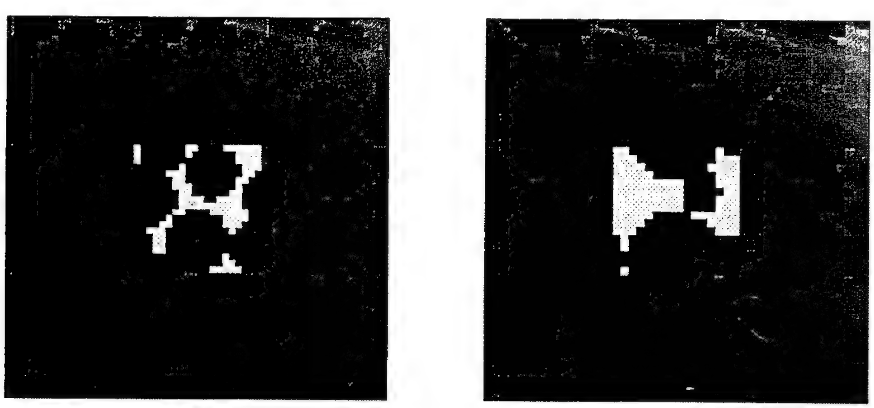


Figure 1. Example Stochastic Sand Grids with 24% and 39% Porosity

As porosity approaches a critical value of about 39%, sand changes from a framework structure to a suspension. Lower porosities imply a level of cementation among grains which is reflected in the analysis grid. The structured grid has a resolution scale which is limited by the grid size. As porosity increases the structure becomes dominated by grain contacts which cannot be well represented by the grid.

Both saturated and dry analyses were carried out for each structure. In the saturated case the pore space is filled with water and in the dry case the pores are empty. The finite element approach assumes that all phases are elastic solids so it is necessary to model water and void spaces as pseudo-elastic solids. The elastic properties used in the sand model are listed in Table 1. Water is modeled as a nearly incompressible elastomer with Poisson's ratio approaching 0.5. The void space is modeled as an elastic material with extremely low modulus. Sand grains are modeled with the elastic properties of quartz.

The MISTRA analysis generates orthotropic elastic moduli for the stochastic sand structures studied. We assume that the macroscopic sediment is isotropic and use a Reuss/Voigt average of the orthotropic moduli to calculate velocity of a random assemblage of elements with orthotropic properties (Christensen 1982).

Figure 2 shows the results of velocity simulations in ten stochastic sand models with porosities ranging from 1 to 39%. Both dry framework and saturated velocities are shown. These numerical data points are compared with the critical porosity model of Yin, Nur and Mavko (1993) which provides an upper bound (curves) to observations of velocity in clean sandstones and sand. The numerical simulations are all quite reasonable. Our previous results, had shown a problem with convergence and overestimates of moduli near the critical point. The new results reflect a more accurate, double precision solver which is capable of dealing with the singularity implicit in an elastic solution for an incompressible medium. MISTRA is capable of modeling the full range of sand behavior from a solid framework through a suspension with porosities greater than 39%..

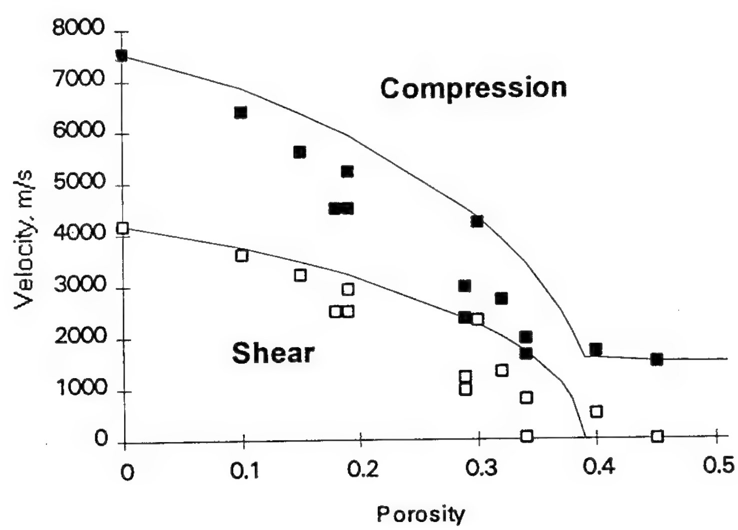


Figure 2. Compression and Shear Wave Velocities in Saturated Sand

GASSY SEDIMENT

A structural modeling analysis of the effect of gas pockets on the acoustic properties of Eckernfoerde Bay mud was carried out using the finite element analysis method. We generated two dimensional structure models based on a CAT scan of a pressurized mud core containing a number of gas pockets (Figure 3, provided by Aubrey Anderson). High contrast image samples, illustrated in Figure 4 were generated from the CAT scan image. The sample structures have porosities ranging from 3.1% to 9.5%. These high contrast images were used to generate structured finite element analysis grids. We also investigated the effects of square pores with a broad range of porosities on mud properties.

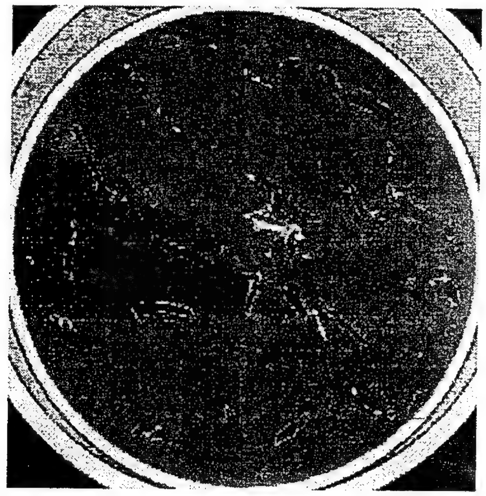
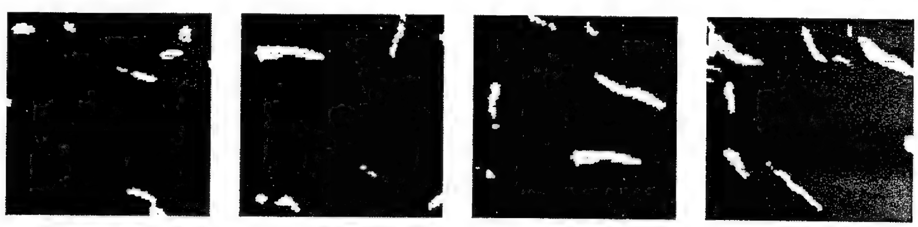


Figure 3. CAT Scan of Eckernfoerde Core 339 - Pockmark Floor ~380 mm Depth.



$\phi =$ 3.1 % 3.9 % 5.1 % 9.5 %

Figure 4. High Contrast Sample Images for MISTRA Analysis

The gassy mud is modeled as a two phase elastic composite. The elastic properties of the matrix (mud) phase were derived from the mean acoustic properties of the sediment in Eckernfoerde Bay as provided by Mike Richardson. Most of the near surface sediment sampled in the study do not contain gas pockets and the sediment density is consistent with this assumption. Elastic properties of the matrix were derived from the compression and shear wave velocities in the sediment. The gas pocket properties were derived from the properties of methane gas trapped at the ambient temperature of the mud using the ideal gas law gas law and pressure and temperature appropriate for Eckernfoerde Bay.

Note that this reverts to the relationship between incompressibility and acoustic wave velocity in a gas when $\nu = 0.5$; A Poisson's ratio of exactly 0.5 causes singularities in the stiffness matrix of the finite element solution for an elastic material, we therefore choose Poisson's ratio to be as close as possible to 0.5 consistent with the accuracy limitations of our computer. This results in a small but finite value for the shear wave velocity in the "gas". Mean Eckernfoerde sediment properties used in the simulations are listed in Table 1.

Table 1. Eckernfoerde Sediment Mean Properties

	ρ, kg/m^3	C_p, m/s	C_s, m/s	K, Pa	G, Pa	ν	E, Pa
mud	1190	1428.6	8.00	2.43×10^9	7.62×10^4	0.49998432	2.28×10^5
"gas"	1.838	429.5	0.02	3.39×10^5	6.78×10^{-4}	$0.5 - 10^{-9}$	2.03×10^{-3}

We then modeled the geometries illustrated in Figure 4 using a structured grid. These results are shown as the four data points in Figure 5. The acoustic velocities given represent the low frequency limit for acoustic wavelengths larger than the scale of the void spaces. In this case, the voids are on the order of up to 10 mm in scale. The velocities are thus valid for compression wave frequencies under 1 kHz and shear wave frequencies under 100 Hz. The MISTRA model data are compared with the Kuster-Toksoz (KT) (1980) model for a dilute suspension of randomly oriented ellipsoids. Ellipse aspect ratios (shown alongside the KT points) were chosen to match the MISTRA data and are reasonable values for the voids shown in Figure 4. The MISTRA compression wave velocities are within 4% of the KT model and the shear velocities agree within 0.5%.

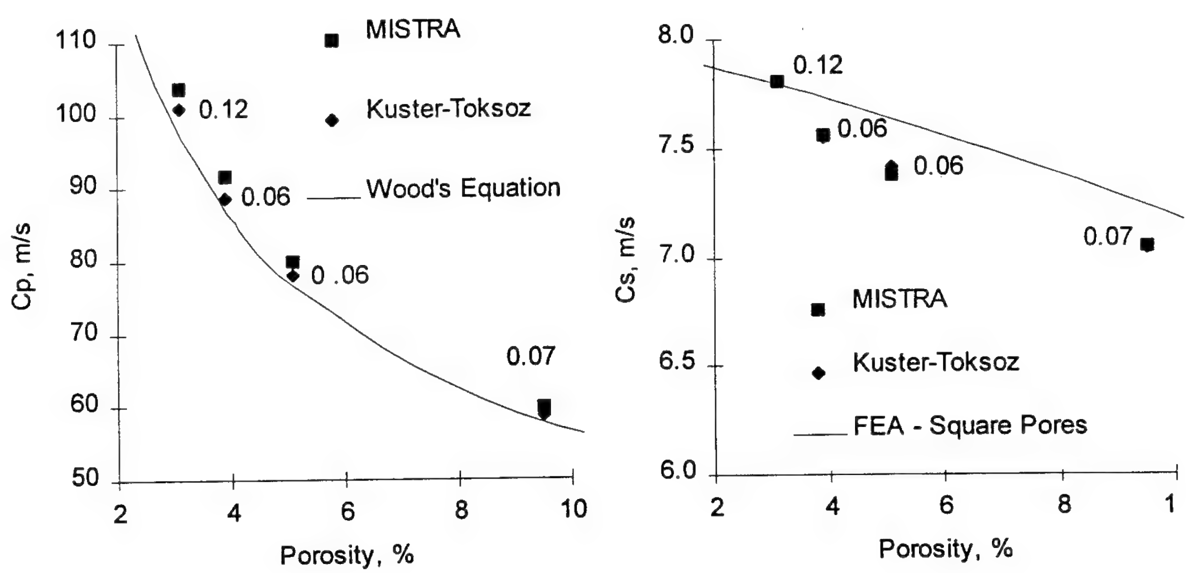
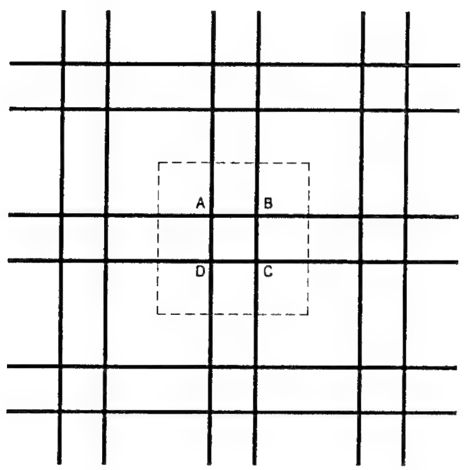


Figure 5. Modeled Compression and Shear Wave Velocities in Gassy Eckernfoerde Sediments

MISTRA was also used to calculate velocities in mud containing square pores to illustrate the influence of pore aspect ratio. There is little difference between predictions for compression wave velocity but a significant effect of pore aspect ratio on the shear wave velocity. The compression wave velocity may also be estimated using the isostress approximation for average compressibility of two fluids (Wood's equation). This relationship does not account for the finite shear modulus of the sediment, but as seen in Figure 5, the result provides a lower bound on velocity.

CLAY MICROFABRIC

Clay can be thought of as a collection of randomly oriented plates which, under weak electrostatic forces, are held together in a skeleton structure. The weak forces are a result of the opposite charges forming on the plate edges and the plate surfaces. The platelet skeleton structure is an interconnected maze through which the water may flow and this water can help to support the skeleton structure under hydrostatic loading.



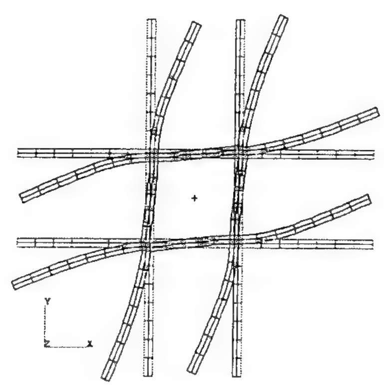


Figure 6. Regular Lattice Structure Showing Pure Shear Deformation of a Hinged/Cantilevered Model

We first examined a very simple unit periodic framework structure shown in Figure 6. The widths of the plates have been chosen so that the porosity of this frame work is close to that of the Eckernfoerde mud of 90.4%. This model consists on nine individual, unconnected pores. To study the frame rigidity, the joints labeled A,B,C, and D have been considered hinged or cantilevered. The model identified as "Fully Cantilever" has all joints cantilevered, the modeled identified as "Fully Hinged" has all joints hinged and finally the model labeled Hinge-Cantilever has joints A and C cantilevered whereas B and D are hinged. All models were been subjected to macroscopic pure bulk strain and macroscopic pure shear strain load and the macroscopic bulk mean stress and shear stress are then computed as an average over all the elements in the model. Table 1 shows the elastic moduli and velocities used to model Illite, water and void spaces.

As one would expect the fully cantilevered model gave the strongest rigidity and the fully hinged model was the weakest. The fully hinged framework (void case) showed no shear rigidity because the platelets could pivot on the hinges. Furthermore, the water saturated fully hinged model showed no shear rigidity

because the plates could pivot in such a way that the individual pores do not change volume. The fully cantilevered model behavior agrees with Gassmann's equations in that the water saturated shear modulus is the same as the frame modulus. This is because the symmetry of the plate deformation is such that the individual pores do not change in volume under macroscopic shear. However, the hinged-cantilevered model shows that the saturated shear modulus is greater than the dry framework modulus. The increase shear rigidity is due entirely because the symmetry is broken and pore volume changes in pure shear. Hence some pores become compressed and others expand giving rise to a differential pore pressure.

Table 2. Material Properties used in MISTRA Analysis of Clay Mud

Material	ρ	*K*	*G*	*Cp*	*Cs*
Illite	2790	5.19×10^{10}	3.09×10^{10}	5780	3330
water	1020	2.16×10^{9}	4.31	1454	0.065
void	1	1.67×10^{2}	3.33×10^{-7}	408	0.0

Not surprising all the simple frame models showed bulk and shear modulus which are larger than measures values of Eckernfoerde mud. To examine the role of the random structure we constructed two slightly different models of a random microstructure which, as before, have approximately 90.4% pore area fraction. The clay platelets were linked in an edge-face structure based on TEM images of Eckernfoerde mud provided by Dennis Lavoie at NRL. Structure "A", shown in Figure 7 was generated by randomly placing randomly oriented clay platelets with an aspect ratio of 20:1. This model is permeable in the sense that a continuous pore space extends horizontally through the center of the model. No such pathway exists in any other directions, hence the model is somewhat anisotropic. This 2D model can not have any framework shear strength since it will slip along this line. For that manner, the modulus for loads acting approximated from to bottom would not be resisted. To evaluate the influence of permeability we slightly modified the platelet structure in Model "B", extending the platelets in order to close the flow and strengthen the framework.

Figure 7. TEM Image of Eckernfoerde Mud and Stochastic Clay Platelet Structure "A" Used for MISTRA Modeling

A series of tests were conducted on both structures assuming joints are fully cantilevered or fully hinged. As in the simple model, differential pressure developed in isolated, non-communicating pores. For example, even though the analysis indicated that framework of structure A-hinged, A-cantilevered, and B-hinged have no shear strength, the fully saturated models do possess some non-negligible strength. Only model B-cantilevered shows some framework shear resistance and yet even in this case, the addition of water tends to promote is shear modulus. A plot of the pressure in the pores under pure shear strain loading shows distinct pressure differentials among isolated (or nearly isolated) pores. To confirm that the differential pressure is responsible for the shear modulus and not the limitations of the pseudo-water assumptions of the analysis we plotted the shear stress in the pseudo-water filled pores and noted that the pseudo-water shear stress magnitude is much smaller than the macroscopic average shear stress.

The hinged model predictions are compared to the measured properties of Eckernfoerde mud in Table 3. All the models do a good job predicting the bulk modulus. This is primarily due to the very weak dry bulk modulus of the platelet framework. The random model as expected predicts a much weaker modulus than the simple models. The very small shear modulus predicted by the random models are much closer to the experimentally observed values than the simple models. In fact the two hinged models bracket the observations of velocity in Eckernfoerde mud. The order of magnitude agreement to the measured values indicates that the framework shear modulus is quite weak and may be negligibly small. The models also points out that the rather small observed shear modulus in Ekernfoerde mud may not simply be the result of the framework, but a combination of the water and frame through the action of differential pressure in isolated pores.

Table 3. Comparison of MISTRA Analysis with CBBL Data

Property	A-Hinged	B-Hinged	Eck. Mud
K_s, Pa	2.38×10^9	2.38×10^9	2.43×10^9
K_d, Pa	0.0	0.0	N/A
G_s, Pa	2.77×10^4	3.81×10^5	6.72×10^4
G_d, Pa	0.0	0.0	N/A
C_p, m/s	1414	1414	1429
C_s, m/s	4.8	17.9	8.0

SUMMARY AND CONCLUSIONS

MISTRA was used to determine poroelastic moduli for three marine sediments encountered during the first two years of the CBBLSRP.

A simple structured grid model of compact sand microfabric showed that saturated and dry framework moduli could be obtained from a finite formulation using pseudo-elastic moduli to simulate water and void space. Single precision, structured grid, MISTRA models of clean sand agree well with data available in the literature over the full range from solid framework through a sand suspension. We found that a double precision solver was required to handle singularities introduced when the shear

modulus of the pseudo-elastic water or void space approaches zero. West Florida sand sheet velocities and microfabric data were not available for this comparison.

Clay microfabric structural analysis required the use of unstructured grids on a double precision computer. The results showed that the MISTRA approach was capable of modeling a clay platelet structure based on TEM imagery of mud from Eckernfoerde Bay. The clay structure models provide saturated moduli which bracket the observed properties. The shear modulus of the clay was shown to be due to differential pressures which arise in isolated pores as the clay framework is distorted. Thus the saturated clay structure can have a non-zero shear wave velocity even though the dry framework moduli are negligible.

Finally MISTRA was used to model gas pocket inclusions in gassy mud from Eckernfoerde Bay. Analyses were carried out on CAT scanned images of pressurized cores. Modeled compression and shear wave velocity anomalies agree well with analytical models of wave propagation in a medium containing ellipsoidal inclusions.

The MISTRA modeling effort has shown that a single finite element analysis procedure can be employed to model poroelastic acoustic properties of all of the sediment microstructures encountered in the first two years of the CBBLSRP including cemented sand, noncohesive sand, sand suspensions, high porosity clay and a clay mud containing gas inclusions. This unified approach can be generally applied to sediment microfabric providing a significant advantage over the contact and inclusion theories currently available for sediment modeling.

REFERENCES

Berryman J.G. (1980) "Long-wavelength propagation in composite elastic media II. Ellipsoidal inclusions," *J. Acoust. Soc. Am.*, **68 (6)**, 1820-1831.

Christensen, N.I. (1982) "Seismic velocities," Handbook of Physical Properties of Rocks, Vol. II, ed. by R.S. Carmichael, 1-228, CRC Press, Boca Raton.

Kuster, G.T. and M.N. Toksoz (1974) "Velocity and attenuation of seismic waves in two-phase media: Part I. Theoretical formulations," *Geophysics*, **39**, 587-606.

Yin, H., A. Nur and G. Mavko (1993) "Critical porosity-a physical boundary in poroelasticity," *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, **30 (7)**, 805-808.

Mueller, A. C and Kollé, J. J. (1991) "General approach to finite-element analysis of composite micromechanics," *Proceedings of the 8th International Conference on Composite Materials ICCM/8, Honolulu*, **3**, paper 29-E, Society for Advanced Material and Process Engineering, Covina, California.

Richardson M.D. (1994) "Investigating the Coastal Benthic Boundary Layer," *EOS, Trans. Amer. Geophys Union.*, **75 (17)**.

Stoll R.D. (1989) "Sediment Acoustics", *Lecture Notes in Earth Sciences*, **29**, ed. by S. Bhattacharji, G.M. Friedman, H.J. Neugebauer and A. Seilacher, Springer Verlag, New York.

Wang Z. and A. Nur (1992) "Elastic wave velocities in porous media: A theoretical recipe," *Seismic and Acoustic Velocities of Reservoir Rocks, Vol. 2, Theoretical and Model Studies, Geophysics Reprint Series*, **10**, ed. by Z. Wang, A. Nur and F.K. Levin, Society of Exploration Geophysics, Tulsa.

FY94 PUBLICATIONS

Two presentations were prepared during FY94. These were published as abstracts as follows:

Kolle, J.J., A.C. Mueller and J. Dvorkin (1994) "Microstructural modeling of clay sediments in Eckernfoerde Bay," *J.Acoust. Soc. Am.*, **96 (5)**, 3246.

Kolle, J.J. Structural analysis of marine sediment microfabric to derive Biot Poroelasticity constants

2.10 The Bragg Condition Limitation on Inversion of Normal Incidence Reflection Data (Principal Investigators: Gilbert and Kulbago)

The Bragg Condition Limitation on Inversion of Normal Incidence Reflection Data
(Principal Investigator: K.E. Gilbert, ARL/PSU)

CBBLSRP FY94 YEAR-END REPORT

Timothy J. Kulbago and Kenneth E. Gilbert
Applied Research Laboratory
Pennsylvania State University
State College, Pa 16804

ABSTRACT

FY94 was the first year of research on this project. In an effort to improve the characterization of the benthic boundary layer by remote acoustic sensing, we investigated the capabilities and limitations of a number of approaches for inverting normal incidence reflection data.[1,2,3] In our investigations, we attempted to answer a fundamental question: "What can be learned about the physical properties of the sediment from a given normally incident broadband acoustic probe signal?" In trying to answer this question we have recently arrived at a simple relation between the impedance profile of a continuously stratified sediment and its acoustic response. The relation allows a straightforward calculation of both the forward and inverse problem, but more importantly, it clearly establishes the "Bragg condition" as a fundamental limitation on any acoustic inversion scheme. For normal incidence backscatter, the Bragg condition says an acoustic wavelength λ senses or "filters out" only the Fourier component of the impedance profile having wavelength $\lambda/2$, i.e., $\lambda_{medium} = \lambda_{acoustic}/2$. In surveying the literature we have found that, surprisingly, many reported inversion results substantially violate the fundamental limit imposed by the Bragg condition. In the space allotted here we focus on the explanation and interpretation of the relation we have derived since it quantifies many of the conclusions of our work in FY94, and, we believe, should provide some useful insights for other researchers in the CBBLSRP.

I. A SIMPLE RELATION FOR THE ACOUSTIC RESPONSE OF A CONTINUOUSLY STRATIFIED SEDIMENT

We have derived a simple relation between the normal-incidence impulse response and the impedance profile of a horizontally stratified sediment. The relation, which is valid when single scattering dominates, is given by:

$$R(t) = [1/4\rho(x)]dZ(x)/dx \qquad (1)$$

where $R(t)$ is the impulse response, $Z(x)$ is the impedance profile, and $\rho(x)$ is the density. Although the relation is simple, it is accurate for reflections near the water sediment interface (0 - 5 m) where the acoustic return is mainly due to single scattering.

In Figs. 1 and 2, we show results for an impedance profile of the form $Z(x) = Z_o[1 + A\cos\alpha x]$ where Z_o is the impedance of water. The parameters A and α control, respectively, the amplitude and the number of oscillations in the profile. [Note that with this simple analytic profile and with $\rho(x)$ set to the density of water, ρ_o, Eq. (1) gives $R(t) = -(\alpha A Z_o/4\rho_o)\sin \alpha x$.] In Figs. 1 and 2, (a) is the impedance profile, (b) is an exact numerical calculation of the impulse response, and (c)

is the approximate impulse response from Eq. (1). In Figs. 1(c) and 2(c), depth is mapped into time by using $x = c_{ref}\, t/2$, where c_{ref} is a reference sound speed. In Fig. 1(c), Eq.(1) gives an accurate result in the first part of the acoustic return. The return from the maximum depth of 6 m is off by approximately 10% of the maximum amplitude. In Fig. 2(c), the same trend holds, with the result from Eq. (1) being accurate near the water-sediment interface where single scattering dominates. In the exact impulse response in Fig. 2(b), as the acoustic wave penetrates into the sediment and multiple scattering builds up, the exact solution decays with time, while in 2(c) the single scattering result obtained from Eq. (1) has a constant amplitude. Even with the single scattering limitation, it is clear from Figs. 1 and 2 that Eq. (1) captures much of the physics of the near-surface impulse response. Consequently Eq. (1) is very useful in understanding the limitations on inversion of normal incidence reflection data.

II. APPLICATION TO INVERSION OF BROADBAND REFLECTION DATA

In the above section we showed the degree of accuracy of Eq.(1) by computing the impulse response given an impedance profile. The procedure can be reversed and Eq.(1) can be integrated to obtain an estimate of the impedance profile from the impulse response. Using $dx = dt\, c(x)/2$ and integrating Eq.(1) gives

$$Z(x) = Z_0 \exp[\, 2 \int_0^{t=2x/c_{ref}} R(t')dt'] \tag{2}$$

For weak scattering, we can linearize Eq. (2) and write

$$Z(x) \cong Z_0 [\, 1 + 2 \int_0^{t=2x/c_{ref}} R(t')dt'] \tag{3}$$

Figure 3 shows shows the result of using Eq. (3) to invert synthetic (computed) data. The actual impedance profile is shown in Fig. 3(a) and is a superposition of the profiles in Figs. 1(a) and 2(a). The impedance profile estimated from Eq. (3) is shown in Fig. 3(b). The synthetic impulse response used in the inversion was computed with the spectrum shown in Fig. 3(c). The maximum error in the estimated profile is approximately 10% of Z_0 and is generally less at smaller depths. The source of the error in the impedance profile is the same as was seen in the forward problem. In the forward problem, the neglect of multiple scattering in Eq. (1) caused the deeper reflections to be too strong. To compensate for over-estimated reflection strengths at larger depths, Eq. (3) yields impedance changes that are too small and the true profile is consequently underestimated for deeper reflections. Nevertheless, near the water-sediment interface, the estimated profile is sufficiently accurate to be useful for many purposes.

III. FUNDAMENTAL LIMITATIONS ON INVERSION OF NORMAL INCIDENCE REFLECTION DATA

In sections I and II we showed that Eq.(1) and its inverse, Eq. (3), give accurate descriptions of the acoustic response of a stratified sediment when single scattering dominates. In the forward and inverse problems considered to this point, the bandwidth of the pulse has been very wide and more than sufficient to encompass all the wavelengths in the vertical structure of the impedance profile. In this section we want to consider the limitations on inversion when the probe signal contains a limited range of frequencies.

To begin the analysis, we set $\rho(x)$ to a constant value of ρ_0 in Eq.(1) and Fourier transform both sides of the equation. Hence for the forward problem we have

$$\tilde{R}(k=\omega/c_{ref}) = (-i/\rho_o c_{ref})\, k\, \tilde{Z}(2k) \tag{4}$$

and for the inverse problem

$$\tilde{Z}(k) = (2i\, \rho_o\, c_{ref}/k)\, \tilde{R}(k/2=\omega/2c_{ref}) \tag{5}$$

where $\tilde{R}(k = \omega/c_{ref})$ is the single frequency complex reflection coefficient (i.e., the frequency response), and $\tilde{Z}(k)$ is the amplitude of the kth wavenumber component of Z(x). It is clear from Eq. (5) that if we probe the bottom with an acoustic signal of wavelength λ, where $k = 2\pi/\lambda$, we measure only the strength of the Fourier component of Z(x) having wavelength $\lambda/2$. That is, with single scattering, since $\tilde{Z}(k)$ is proportional to $\tilde{R}(k/2)$, the Bragg condition holds rigorously:

$$\lambda_{medium} = (1/2)\, \lambda_{acoustic} \tag{6}$$

For a probe signal containing a spread of wavelengths, λ_{min} to λ_{max}, the inverted impedance profile can contain only wavelengths between $\lambda_{min}/2$ and $\lambda_{max}/2$. This important point is illustrated in Figs. 4 and 5. The actual profile is the same as that in Fig. 3, that is, it contains a long wavelength component ($\lambda_{medium} \approx 12$ m) and a short wavelength component ($\lambda_{medium} \approx 1$ m). In the previous inversion, in Fig. 3, the spread of wavelengths contained in the probe signal was sufficient to encompass both the long and short wavelengths in the impedance profile. Consequently, in Fig. 3(b) the actual profile was faithfully recovered. In the inversion shown in Fig. 4, the probe signal contains only frequencies below 500 Hz so that $\lambda_{acoustic} > 3$ m. As a result, only the long wavelength component of the impedance profile is recovered in the inversion. Conversely, in Fig. 5, where the probe frequencies are between approximately 500 Hz and 1000 Hz (1.5 m $< \lambda_{acoustic} <$ 3 m), the reflected wave is sensitive only to the short wavelength component. Consequently, the "trend" represented by the long wavelength component is absent in the inversion.

IV. CONCLUSIONS

The Bragg condition, $\lambda_{medium} = \lambda_{acoustic}/2$, imposes a requirement for a large bandwidth for normal incidence probe signals if any fidelity is to be obtained in the inferred impedance profile. In particular, to obtain trends in impedance that occur over meters requires frequencies with wavelengths of approximately twice the desired trend distance. If high frequency (kHz and above) probe signals are used for normal incidence inversion, an accurate non-acoustic constraint is needed in order to reliably connect the short wavelength components of the impedance profile (which are acoustically sensed) to the long wavelength components of the profile (which are not acoustically sensed). Many of the high frequency inversions reported in the literature show trends with wavelengths orders of magnitude larger than any wavelength in the probe signal. It is worthwhile to ask whether the long wavelength trends, which cannot be acoustically sensed by the short wavelength probe signals, are the result of a physically meaningful non-acoustic constraint, or whether they are artifacts of arbitrary underlying assumptions in the signal processing method.

REFERENCES

1. T.J. Kulbago and K.E. Gilbert, "A numerical study of normal incidence acoustic backscatter from gassy sediments." Presented at the Ocean Sciences Meeting, American Geophysical Union, San Diego, 1994.

2. T.J. Kulbago and K.E. Gilbert, "Inversion of normal incidence backscatter data from gassy sediments." Presented at the 127th meeting of the Acoustical Society of America, Cambridge, 1994.

3. K. E. Gilbert, T. J. Kulbago, and P. J. White, "A structure function constraint for stable least-squares inversion of reflection data." Presented at the 128th meeting of the Acoustical Society of America, Austin, 1994.

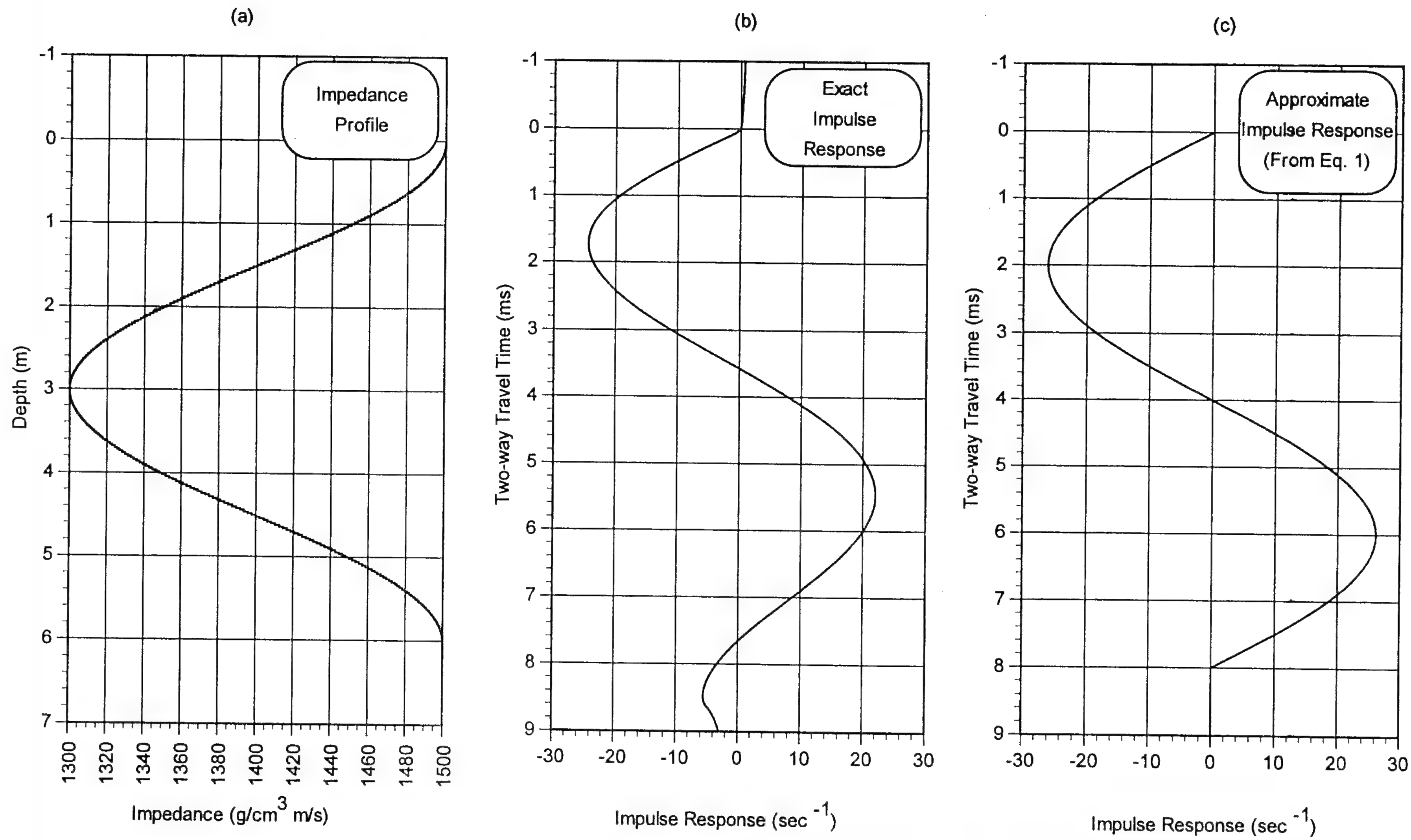


Figure 1. (a) Impedance versus depth (b) Exact impulse response for the impedance profile shown. (c) Approximate impulse response estimated from Eq. 1. Note that the impulse response is proportional to the depth derivative of the impedance profile.

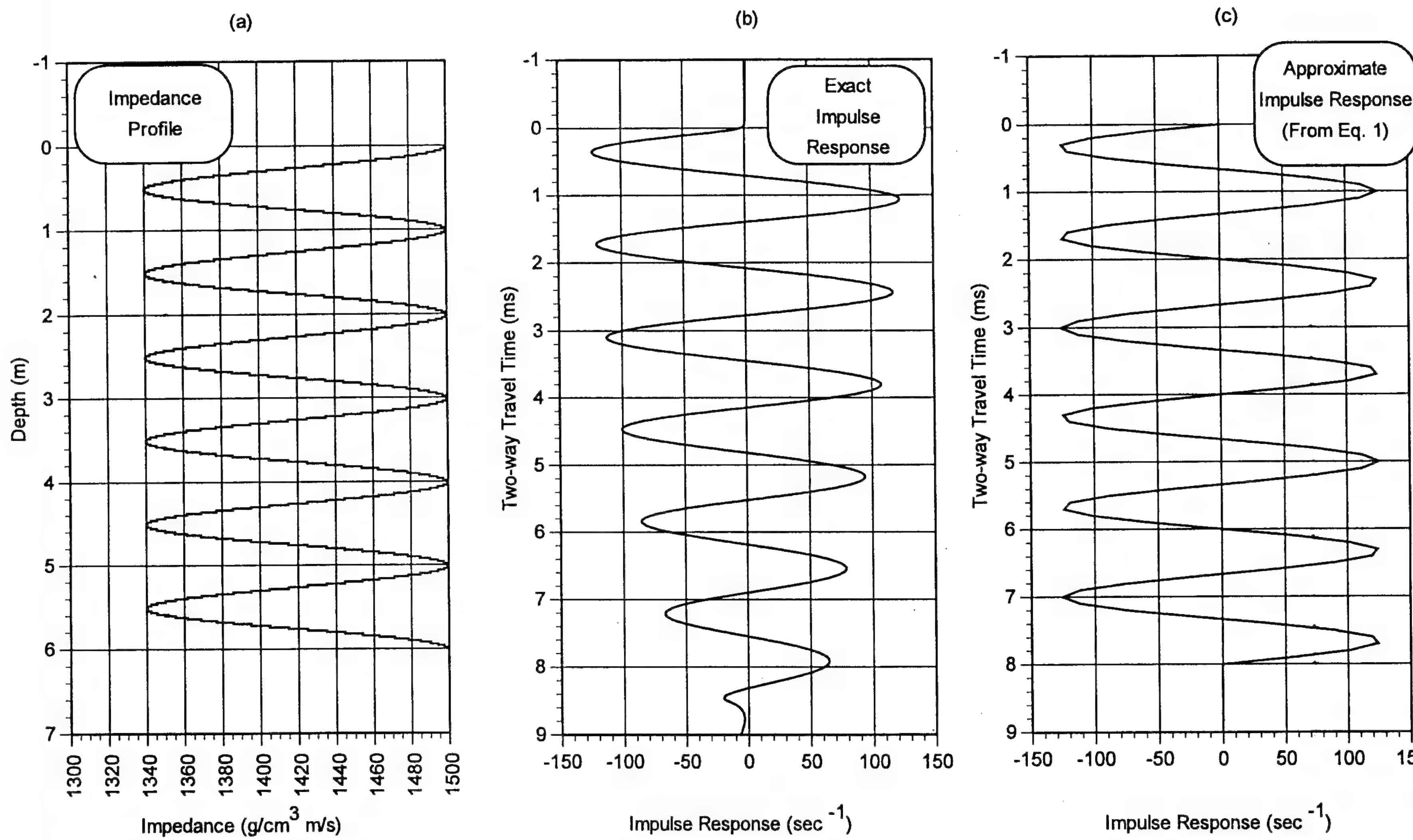


Figure 2. Same as Fig. 1 except a more oscillatory impedance profile is used as input. The difference between (b) and (c) is due to the neglect of multiple scattering in (c).

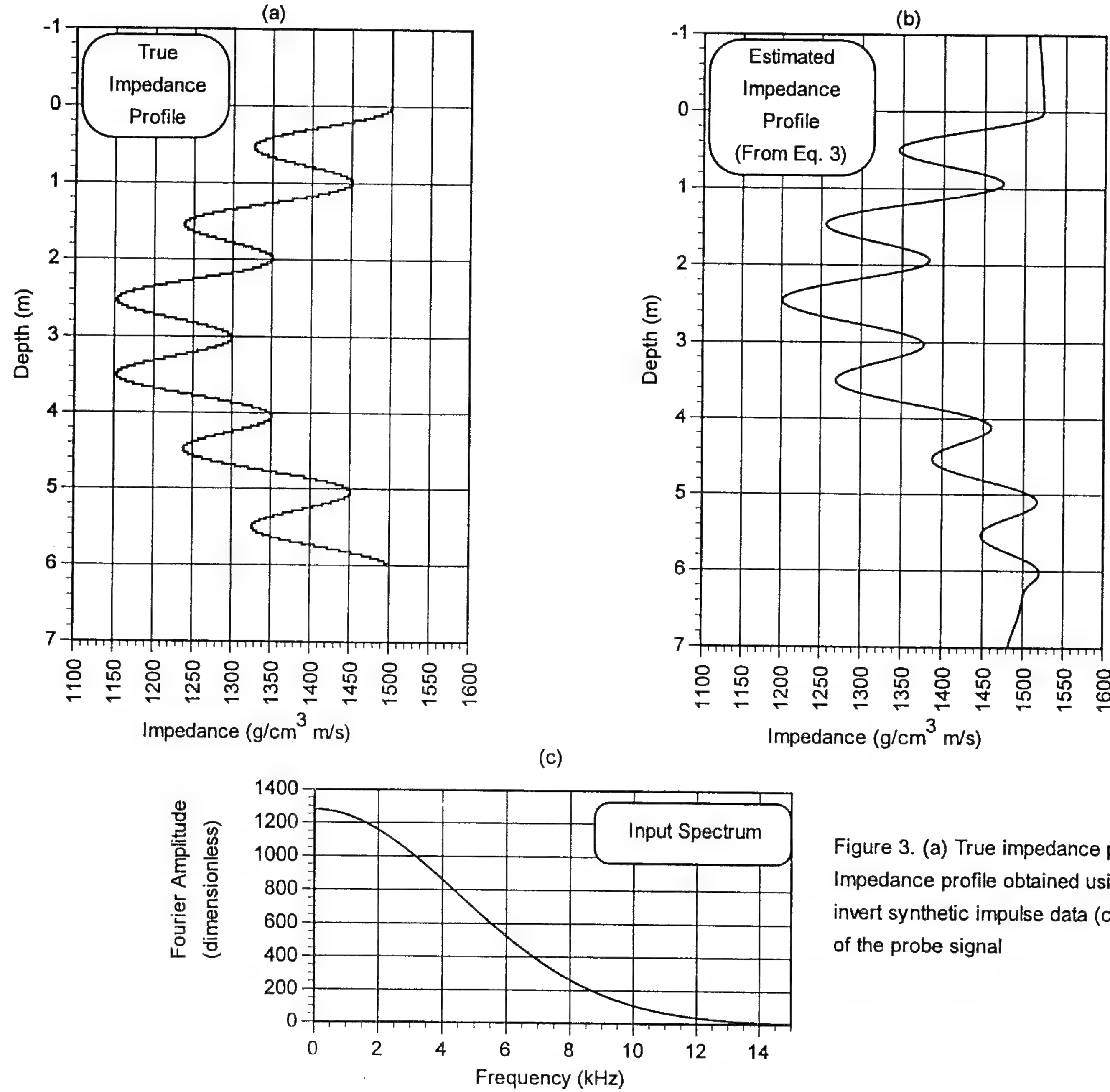


Figure 3. (a) True impedance profile (b) Impedance profile obtained using Eq. 3 to invert synthetic impulse data (c) Input spectrum of the probe signal

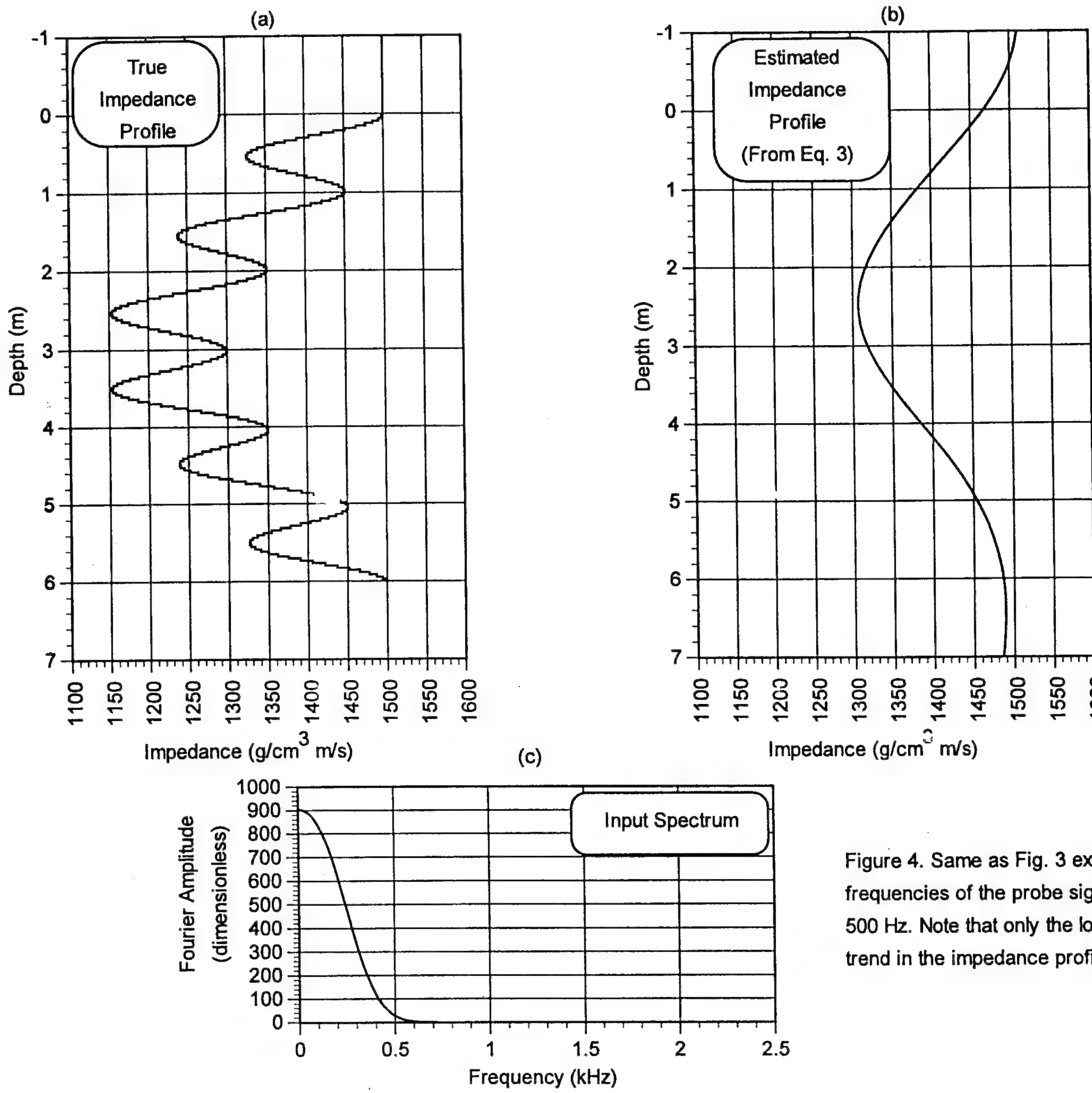


Figure 4. Same as Fig. 3 except the frequencies of the probe signal are less than 500 Hz. Note that only the long wavelength trend in the impedance profile is recovered.

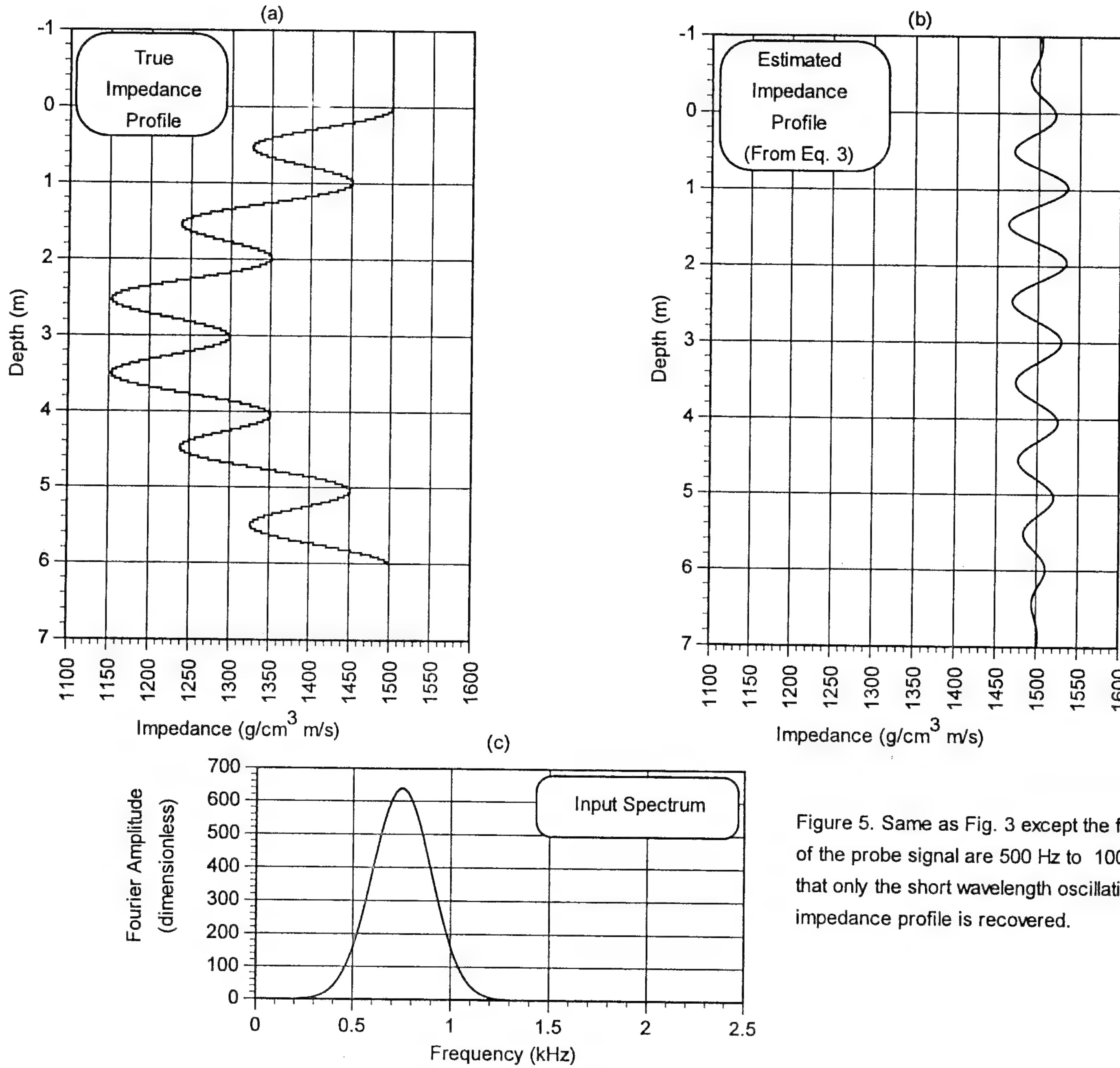


Figure 5. Same as Fig. 3 except the frequencies of the probe signal are 500 Hz to 1000 Hz. Note that only the short wavelength oscillation in the impedance profile is recovered.

2.11 Effects of Environmental Processes on Shear Modulus (Principal Investigators: D. Lavoie and H.A. Pittenger)

CBBLSRP YEAR END REPORT: Effects of Environmental Processes on Shear Modulus

Contributors: Dawn Lavoie and H. Alan Pittenger
Naval Research Laboratory, Code 7431
Stennis Space Center, MS 39529-5004

INTRODUCTION

This report summarizes the work done under this project as part of the Coastal Benthic Boundary Layer Special Research Program during FY94. This project, originally titled "Measurement of Shear Modulus In Situ and in the Laboratory" is now newly retitled to reflect the change in principle investigators. Dr. Alan Pittenger has completed his post doctoral research at NRL; some of his results are included in this report. Dr. Yoko Furukawa, a geochemist has joined the team. Recognizing the importance and interrelationship among physical and chemical properties and microstructure, we are cooperating closely with Dr. Richard Bennett and Dennis Lavoie.

OBJECTIVES

Our long term objectives are to (1) investigate gradients of shear modulus in the field on the cm scale using a duomorph probe, (2) examine shear modulus as a function of direction in the field and in the laboratory in our instrumented triaxial cells where the shear and compressional wave velocity can be measured with the three principle stresses carefully controlled, and (3) relate in situ shear modulus with other geotechnical and geochemical properties and microstructure.

Our short term goals for FY94 were to continue the development of the DIAS system, deploy the system in Key West and again in the Baltic sea, and to continue our analyses of in situ and laboratory data. The system has worked well, although the probes appear not to be as rugged as we would like. We have had to repair and refabricate new probes after each trip. In addition, because the field schedule has been very heavy, we have not been able to calibrate them as carefully as we would like using local sediments. Therefore, one of our main priorities during FY95 will be an intensive effort to calibrate the probes, initially using Shell 200 wax which has very well known properties, and examine the effects of the potting compound in which the probes are embedded.

PROGRESS

During the past two years we have successfully modified the duomorph such that the instrument can be used as an in situ probe. We have fielded this system, DIAS (Duomorph In-Situ Acquisition System), in Eckernfoerde Bay (May, 1993), off Panama City, Florida (August/September 1993), in the Chesapeake (October, 1994), and off the Marquesas and Dry Tortugas (January/February, 1994) and again in Eckernfoerde Bay (June 1994).

Panama City, Florida

The heterogeneous nature of sediment, which is the norm rather than the exception, affects acoustic propagation and must be accounted for in acoustic modeling efforts. One of our goals during the Panama City cruise was to describe the variability of the sand bottom in terms of geoacoustic and geotechnical properties. The DIAS system was deployed at the same sites as the compressional and shear wave velocity systems (Richardson) and a geophysical array measuring shear wave velocity (Stoll). Cores were recovered so that comparisons could be made between the laboratory and in situ properties and to provide values of sediment mass properties.

Samples from the test area are sands with only 1-2 percent clay and silt. Quartz is, by far, the predominate constituent. Carbonate grains (Peneroplid, Miliolid, serial, and biserial foraminifera, along with a variety of algae and shell fragments) make up 5 to 10 percent of the bulk composition. Feldspar (predominately microcline and occasionally plagioclase), along with a variety of heavy minerals, total 1-2 percent. Textures are sub-mature, i.e., contain less than 5 percent clay with poorly sorted and angular grains (Figure 1). The samples are typical of the MAFLA shelf sand in terms of composition (Ludwick, 1964), and texture (Doyle and Sparks, 1980).

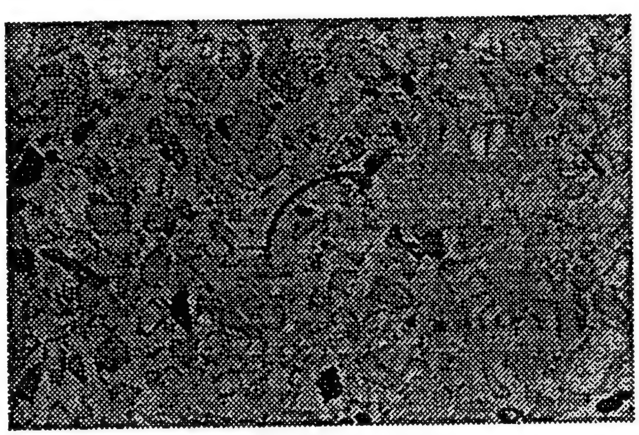


Figure 1. Photomicrograph in plane light (2.5X) of sand from diver core PC554-1 illustrating typical fabric and constituents.

A rough comparison of field results suggests that it is difficult to distinguish between the fine/medium sand (1.5ϕ - 3ϕ) and coarse shelly sand (<1ϕ) based on probe-measured values of shear wave velocity. Shear modulus gradient in the fine sands was determined by combining results from the three deployments of the DIAS probe and (Figure 2). The DIAS data in the coarse sands was extremely erratic, suggesting that the probes do not couple well in coarse sediments.

A comparison of shear wave velocity (1) calculated from the DIAS-measured shear modulus, (2) measured using shear wave probes on the ISSAMS (Richardson), (3) inverted from geophysical data (Stoll), and (4) predicted using Hamilton's regression equations (1980) and using Bryan and Stoll's model for unconsolidated sediments is shown on figure 3. The measured velocity using in situ probes is higher than either the geophysical data or the model-predicted values.

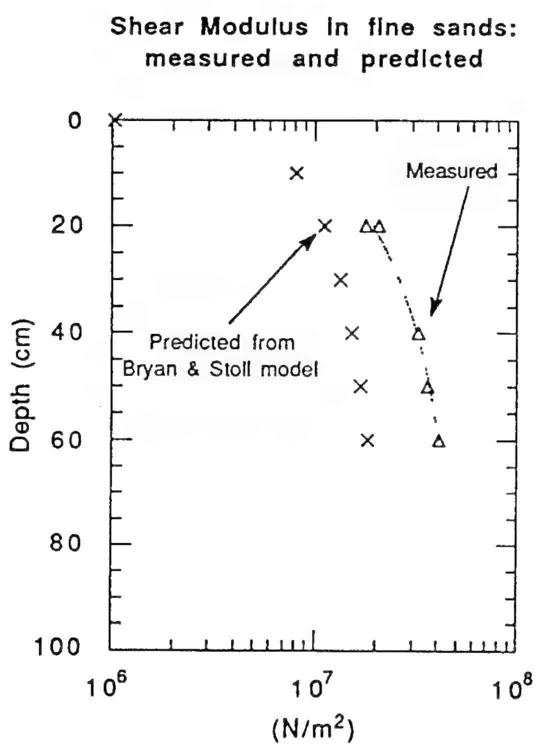


Figure 2. Shear modulus gradient in fine sand measured using the DIAS system, and predicted using Bryan and Stoll's model for non-specific sediments.

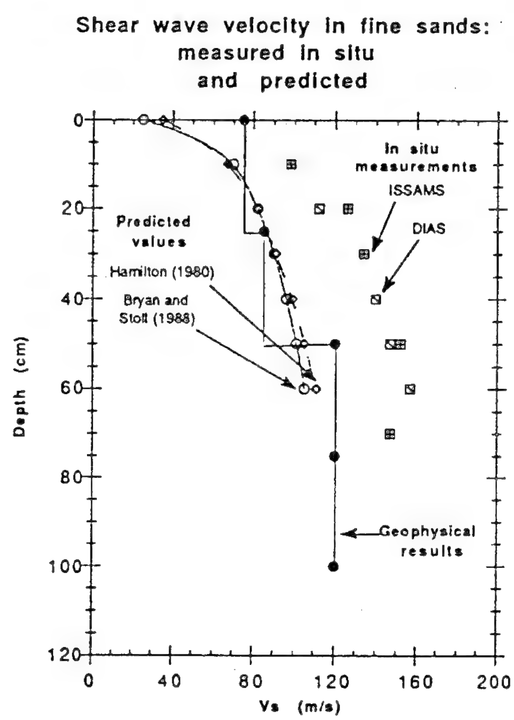


Figure 3. Sear wave velocity in fine sands (1) calculated from DIAS shear modulus, (2) measured using ISSAMS, (3) inverted from geophysical results and (4) predicted using Hamilton's regression equations (1980) and Bryan and Stoll's model (1988).

Laboratory values of shear velocity are ~100 m/s with the sample saturated at 100 kPa back pressure and an equal pressure applied to the triaxial cell, which are high compared to predicted values using a model developed by Bryan and Stoll (1988) for nonspecific lithologies Little consolidation occured with large increases in effective stress; however, both compressional wave velocity and shear wave velocity increased significantly more than would be predicted from the degree of consolidation observed.

Chesapeake Bay

The objective of the November experiment off the Pautuxent River was to characterize a small area for the Naval Surface Warfare Center-White Oak to support modeling studies and field performance tests of mine burial in shallow water coastal sediments (Bennett et al., 1995). As such, this opportunity to use the DIAS system in a slightly gassy, silty-clay environment fit in well with the rest of our CBBL studies and provided an opportunity to compare Eckernfoerde and Chesapeake sediments. Four deployment sites were chosen at which 29 sediment cores were collected in clusters. In situ acoustic measurements of shear modulus were collected at each site.

Although the core sites were closely spaced, grain size analyses reveal that the sediments are quite variable not only among cores but also within each core. Shells and shell fragments were common in several of the cores and wood chips were observed in some of the cores. Most cores revealed a significant percentage of sand size material near the bottom of the cores and the general trend is an increase in the percentage of sand with increasing subbottom depth. Sediment analyses of the interface material revealed high organic carbon contents (10%), high water contents (>400% of dry weight in the upper 0-2 cm), low wet bulk densities, and fine-grain sizes. The percent gas (volume of gas per unit volume of sediment) ranged between 0.5 and 3.0 % of total volume. Assuming the ideal gas law applies to the free gas in sediment, the volume of gas in situ can be corrected. At 12 m water depth the pressure increase is an additional 1.19 atm and the free gas volume present would be about one half the volume measured in the lab (Bennett and others, 1995).

The DIAS system was deployed to complement our laboratory analyses. Shear modulus and shear wave velocity results using the DIAS system (Figures 4 and 5, example data from Site 4) are lower in all cases compared to values obtained from the Panama City sands, and higher than values obtained in Eckernfoerde Bay sediments. For a full report, see Bennett and others, 1995.

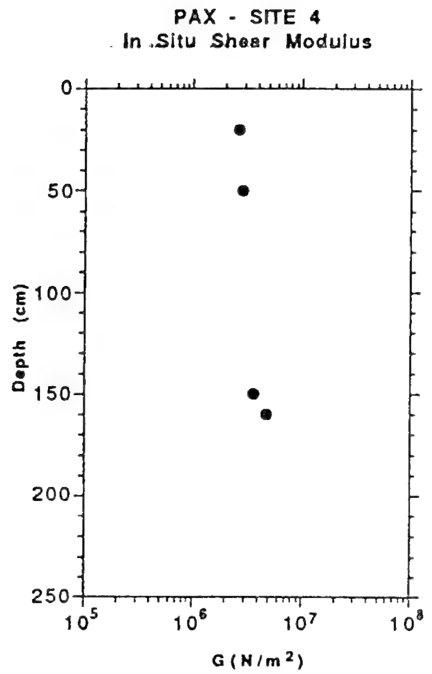


Figure 4. In situ measurements of shear modulus made with the DIAS system at Pax River Site #4.

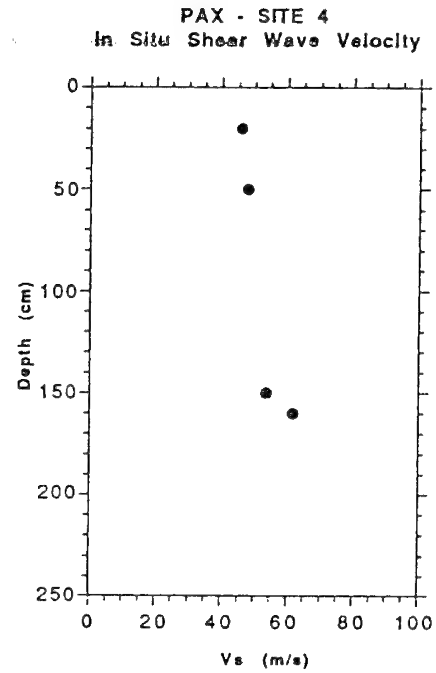


Figure 5. Shear wave velocity calculated from shear modulus values using a density of 1.25 g/cm3 from Site #4.

Marquesas and Tortugas

The primary objective of the January 1994 cruise off Key West was to select appropriate sites for the upcoming FY95 CBBL and MTEDS experiments. Ideally, two sites were to have been picked; one as homogeneous as possible and controlled by biological and chemical diagenesis, the other site to be hydrodynamically controlled. Much of the time was spent surveying using the MACAS (magnetic profiling system) and ASCS (see Lambert and others) systems. Survey data south of the Keys as far west as Rebecca Shoal revealed the bottom to be hardground, very sparsely covered with sediment until we reached the edge of the Quicksands. The sands (primarily Halimeda) fined to the west from the Quicksands and formed large mobile sand waves. The region between the Quicksands and Rebecca Shoal was chosen as a good site to test MTEDS equipment; however, the weather in January and February makes this unprotected area rough except in the periods between fronts. The Marquesas site, which was eventually chosen as a secondaary CBBL site, is a packstone with a fine-grained, silty-clay matrix and numerous shells, some quite large. The sediment is coarse sand near the southern edge of the site and fines to the north. Water depth is 60 to 90 feet within the site with the ideal bottom in the deeper portions of the site.

The primary site chosen for the CBBL experiment is in the Southeast Channel of the Dry Tortugas. Sediments are being transported south through the Tortugas and are ponding in the channel and to some distance southward. Sediments are somewhat finer grained than in the Marquesas site although still packstone. Shelly material seems to be smaller in size than that recovered in the Marquesas. The bottom is well populated with burrowing fauna. Water depths are similar to those in the Marquesas site; however, the Tortugas site is very well protected from the northers and work should be possible throughout the time allotted for the February experiment.

The DIAS system was deployed in both sites; 157 CTD measurements and 101 sediment samples (Smith-Macintyre grabs and gravity cores) were recovered (see Key West cruise report, FY94, and sample listing for a more complete description of experiment results).

Eckernfoerde Bay

A comparison of microfabric and physical properties in Eckernfoerde Bay illustrates the cooperative work we are doing in conjunction with Bennett and others. Unlike other marine sediments studied as part of this project, bulk permeability in Eckernförde Bay sediment appears to be more controlled by the large-scale pores and channels (see D.M. Lavoie) than by the porosity of the microfabric within the clay particle aggregates. The extensive network of large pores and channels is undoubtedly responsible for the high permeability of this sediment, as well as the rapid dissipation of induced overpressure seen in the piezometer results (Bennett et al., 1995). In this respect, and in the shear modulus results, the sediment behaved as one having a coarser grain size than that indicated by the grain size analysis. The structure suggests that permeabilities should also be less in the aggregates, which may have implications for the geochemistry and diagenesis of this sediment.

The observed structure can be expected to have little initial mechanical strength. With application of stress and initial collapse of the pore network, the load should be taken up by the microfabric of the clay particle aggregates. Although the higher density of aggregate microfabric indicates that it should be stronger than the initial structure, the preponderance of edge-to-edge contacts among the clay particles suggests that the microfabric of the aggregates constitutes a relatively weak structure (Bennett and Hulbert, 1986) that would continue to compact under stress (although at a slower rate) due to realignment of the clay domains and the formation of stronger bonds due to the more uniform distribution of clay particles. Such a mechanism is similar to that proposed by Yong (1972, cited in Bennett and Hulbert, 1986, page 77).

The measurements of permeability, void ratio, and shear modulus provide evidence of the existence of this mechanism. In the consolidation data, bulk permeability and void ratio decreased rapidly with the application of small effective stress in an apparent two-stage process (Figure 9) Shear modulus increased after remolding, rather than decreasing, as in normally consolidated sediments. Finally, image analysis of remolded sediment revealed statistically significantly decreased porosity compared to the unremolded sediment, confirming the visual impression of fewer large pores and channels.

PLANS

Our goals for FY95 and 96 are very specific. In the laboratory we intend to (1) calibrate the duomorph probe and make a more detailed study of the probe transfer function (not completed within FY94), and (2) continue our triaxial and oedometer testing in order to quantify the magnitude of difference between measurement techniques for different sediment types and loading conditions. Since our plans for FY95 include participating in the Key West cruise, a carbonate environment, we also plan to examine the effects of diagenetic alteration on the physical and acoustic properties by analyzing the pore fluid chemistry, texture, microstructure (for cements and overgrowths) and mineralogy of the sediments.

PUBLICATIONS

Bennett, R.H., D.L. Lavoie, D.M.Lavoie, W.B. Sawyer, N.W. Hunter, M.M. Meyer, C.S. Kennedy, and K. McCrocklin, Mass Physical and Mechanical Properties of Sediments from the Chesapeake Bay near the Mouth of the Patuxent River, NRL Report (in review).

Lavoie, D.L., S.R. Griffin, and F.B. Grosz, DIAS - a Novel Technique for Measuring In Situ Shear Modulus. Geomarine Letters (submitted)

Lavoie, D.L., R.D. Stoll, M.D. Richardson, H.A. Pittenger, and E.O. Bautista, West FloridaSand Sheet: Geoacousstic and Geotechnical Variability. Geomarine Letters (submitted)

Lavoie, D.M., D.L. Lavoie, H.A. Pittenger, and R.H. Bennett, Bulk sediment Properties Interpreted in Light of Quantative and Qualitative MicrofabricAanalysis. Geomarine Letters (submitted)

Pittenger, H.A., and D.L. Lavoie, Determination of Compressional and Shear Wave Velocity during Triaxial Compression: a Laboratory Manual, NRL/MR/7431—93—7078 23 pp.

CRUISE REPORTS/SAMPLE LISTINGS

Panama City - Coastal Benthic Boundary Layer Cruise, Trip Report for the CBBLSRP Panama City Exeriment, Dates: 9 August to 4 September

Key West - Joint 6.1/CBBL/MTEDS Cruise Report, Dates: 18-January - 17 February

ABSTRACTS

Lavoie, Dawn and Alan Pittenger. 1994. Measurement of Shear Modulus using DIAS. AGU Ocean Sciences Meeting, San Diego, CA.

Lavoie, Dawn, Dennis Lavoie, Richard Bennett, and Alan Pittenger, 1994. Microfabric Predictors of Sediment Properties. Gassy Mud Workship, FWG, Kiel,

REFERENCES

Doyle, L.J, and Sparks,, T.N., 1980, Sediments of the Mississippi, Alabama, and Florida (MAFLA) continental shelf. Journal of Sed. Pet., 50(3):905-915.

Ludwick, J.C. 1964, Sediments in Northeastern Gulf of Mexico. In:Miller, R.L. (ed.) Papers in Marine Geology: Macmillan, 204-238.

2.12 Quantification of Gas Bubble and Dissolved Gas Bubble and Concentration in Organic-Rich, Muddy Sediments (Principal Investigators: C.S. Martens and D.B. Albert)

CBBLSRP FY94 YEAR-END REPORT

Christopher S. Martens
Daniel B. Albert

Marine Sciences Curriculum
CB#3300, 12-7 Venable Hall
University of North Carolina
Chapel Hill, NC 27599-3300

1994 Eckernförde Expedition

Our 1994 activities centered around the June expedition to Eckernförde Bay. On this trip we focused on biogeochemical characterization of three sites of interest for their contrasting geoacoustical properties caused by varying degrees and/or depths of methane saturation. The NRL site occupied during the Helmsand mooring in 1993 was our primary site both this year and last. Methane concentrations reach saturation *in situ* at about 75 cm below the sediment-water interface at this site. In contrast, at the pockmark site sampled this year, saturation occurs much nearer the interface. The acoustic window, as suggested by the acoustic data, does not reach methane saturation in spite of being surrounded by saturated sediments.

During the cruise, emphasis was placed on measuring rates of sulfate reduction, methane production and methane oxidation as well as ship board analysis of methane and ΣCO_2 via headspace analysis. Methane and ΣCO_2 samples were also taken for stable carbon isotopic analysis. Porewater samples were obtained for later measurement of sulfate and chloride. Solid phase samples were taken for downcore elemental analysis (C, N, S) and stable carbon isotopic analysis.

METHANE CONCENTRATIONS AT THE NRL SITE

In 1994, as in 1993 the methane concentration profile at the NRL site showed low concentrations in the upper 35 cm of sediment in which sulfate was present in the pore waters (Figure 1). Methanogenic bacteria cannot compete with sulfate reducing bacteria so their activities are confined to sulfate-free sediments. Below the depth of sulfate depletion the methane concentration rose rapidly and stabilized at about 1 meter depth. The concave-up shape of the methane profile at the base of the sulfate reduction zone is indicative of methane oxidation occuring within this zone. Rates of methane oxidation were measured again this year and we expect to see a peak in oxidation at 30-40 cm depth when these samples are processed. Anaerobic methane oxidation within the sulfate reducing sediments at this site appears to provide a nearly quantitative sink for the methane produced in the deeper sediments.

In Figure 2 methane data from two box cores and a gravity core are combined to show the overall profile to a depth of 4.25 m. The calculated methane saturation line is also shown. Saturation occured by about 75 cm at this site and below 1.25-1.5 m the concentrations fell below saturation except for one datum at 3.25 m. These data thus suggest that methane bubbles would have been confined to a layer between about 75 and 125-150 cm. Pore water salinity (based on chloride) is also

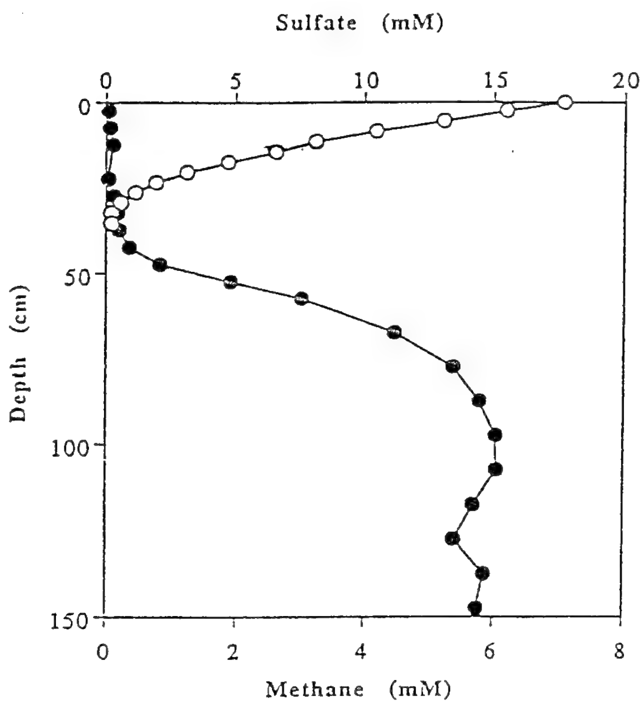


Figure 1. Methane and sulfate concentrations at the NRL site.

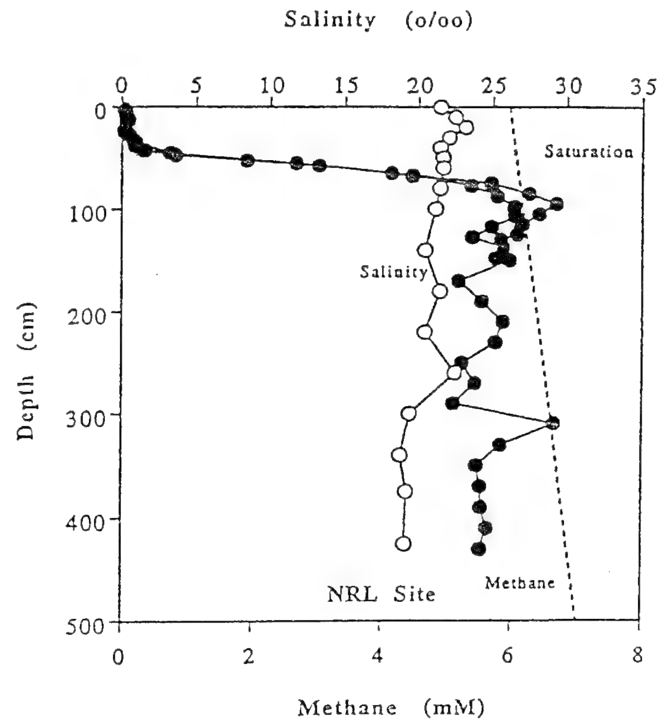


Figure 2. Methane concentrations and salinity at the NRL site showing the calculated methane saturation line.

plotted on Figure 2. There was a slight freshening of the pore water evident between the sediment-water interface (~22 $^{o}/oo$) and the bottom of the core (19 $^{o}/oo$), indicative of slow upward advection of fresher water from below.

METHANE CONCENTRATIONS AT AN ACOUSTIC WINDOW

The acoustic window site is so-called because, unlike the gassy sediments surrounding it, it was acoustically transparent, allowing sound energy to pass through to reflective layers below. This is due to the absence of gas bubbles in the sediments as is shown by the methane concentration profile we obtained in June 1994 (Figure 3). Concentrations rose rapidly below about 25 cm depth and peaked at about 150 cm, but never reached saturation, as indicated by the dashed line. The rise in the saturation line with depth is caused by the increased pressure due to depth as well as the significant freshening of the pore water with depth (methane is more soluble in fresh water). Here salinity dropped from 23 $^{o}/oo$ at the interface to less than 1 $^{o}/oo$ at 413 cm, indicating a more significant advective flow of freshwater from below than was apparent at the NRL site. This flow explains the drop in methane concentrations below 150 cm depth. Methane production rates decrease with depth so the steady-state concentration that can be maintained with a given upward flow of pore water must also decrease with depth.

METHANE CONCENTRATIONS AT THE POCKMARK

At the pockmark methane concentrations rose rapidly just below the sediment-water interface, suggesting sulfate reduction activity in these sediments

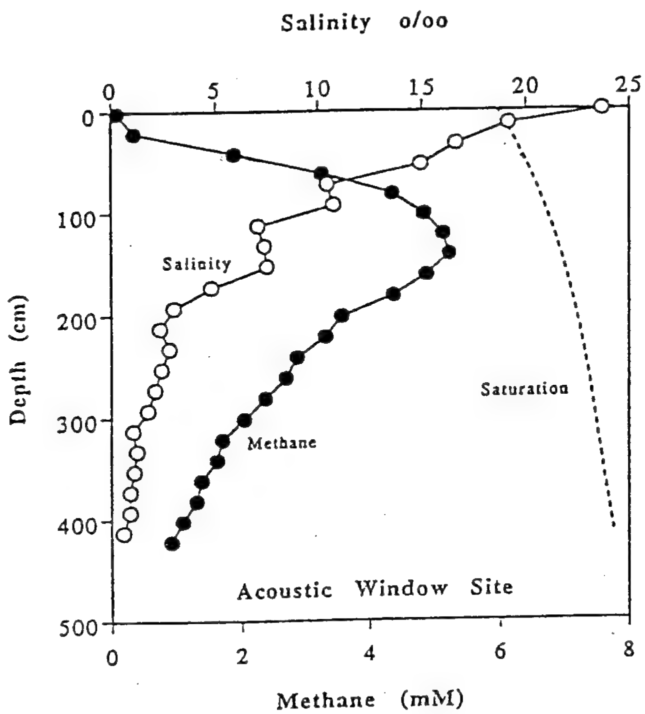


Figure 3. Methane and salinity profiles at the acoustic window.

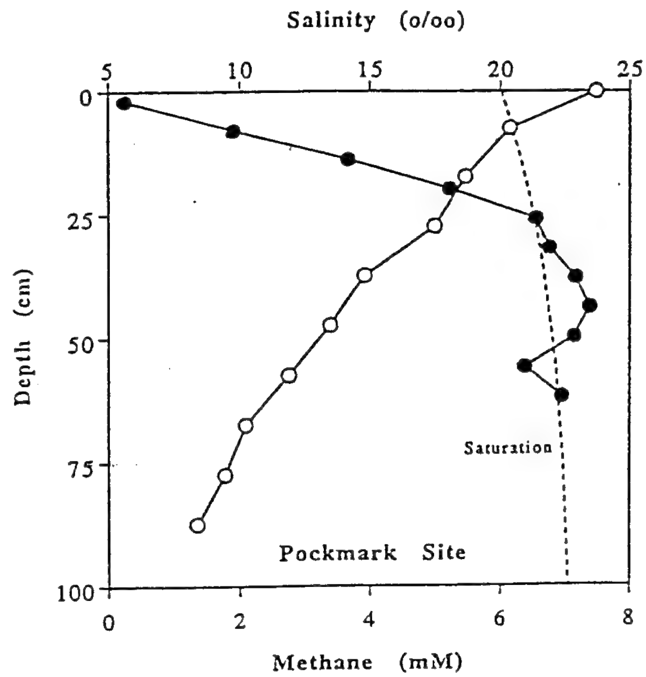


Figure 4. Methane and salinity profiles at the pockmark.

was limited to very near the interface. This was corroborated by sulfate concentration profiles which showed sulfate was depleted by less than 13 cm depth (the sampling interval was too crude to place it exactly). Methane reached saturation at about 25 cm at this site and this was maintained down to about 150 cm, below which concentrations decreased (not shown). This decrease, as at the acoustic window, can be explained by upward advection of fresher (and initially methane-free) water from below and decreasing production rates with depth.

An overall comparison of the methane profiles at the three sites is shown in Figure 5 which clearly illustrates the differences between them. We do not yet have comparative data on the organic carbon and nitrogen content of the sediments at these sites, but given their close physical proximity to one another and similar depths we feel that the organic carbon inputs to these sites are probably very similar to one another. Thus, the very different methane profiles require an explanation divorced from arguments about organic substrate supply. We feel that the explanation lies in the salinity (chlorinity) data from the sites. Plotted together in Figure 6, the salinity profiles from these sites are as different as their methane profiles.

A diffusion-controlled profile for pore water salinity variation between a freshwater endmember at depth and a saline endmember in the overlying water would lie on a straight line between them. Upward advection leads to the curvature we see at these sites. This flow is obviously fed by an aquifer in the glacial till that underlies the fine-grained sediments of the bay.

To calculate the advection rates required to yield the measured chlorinity profiles we used an advection-diffusion model (Berner, R. A., 1980. *Early Diagenesis*, Princeton). The measured profiles were assumed to be at steady-state, under which

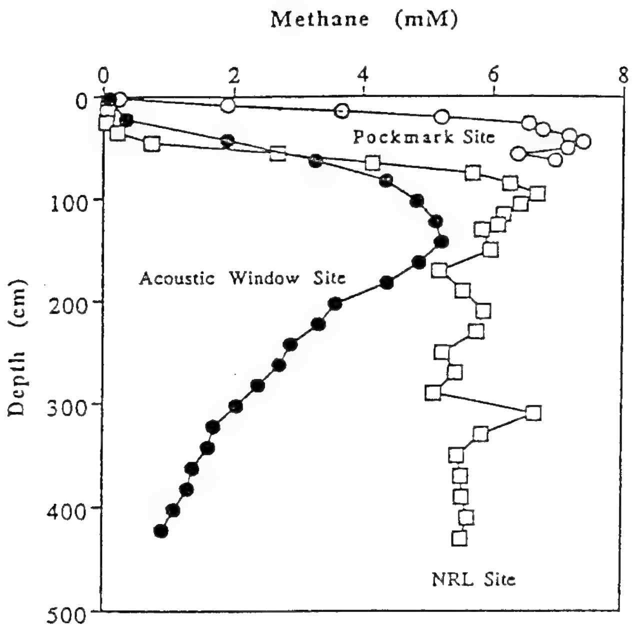


Figure 5. Overlay of methane profiles from the three sites.

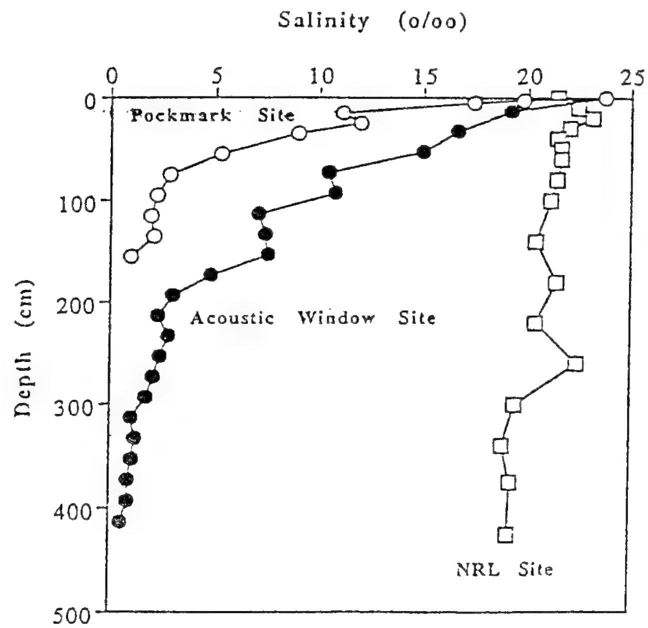


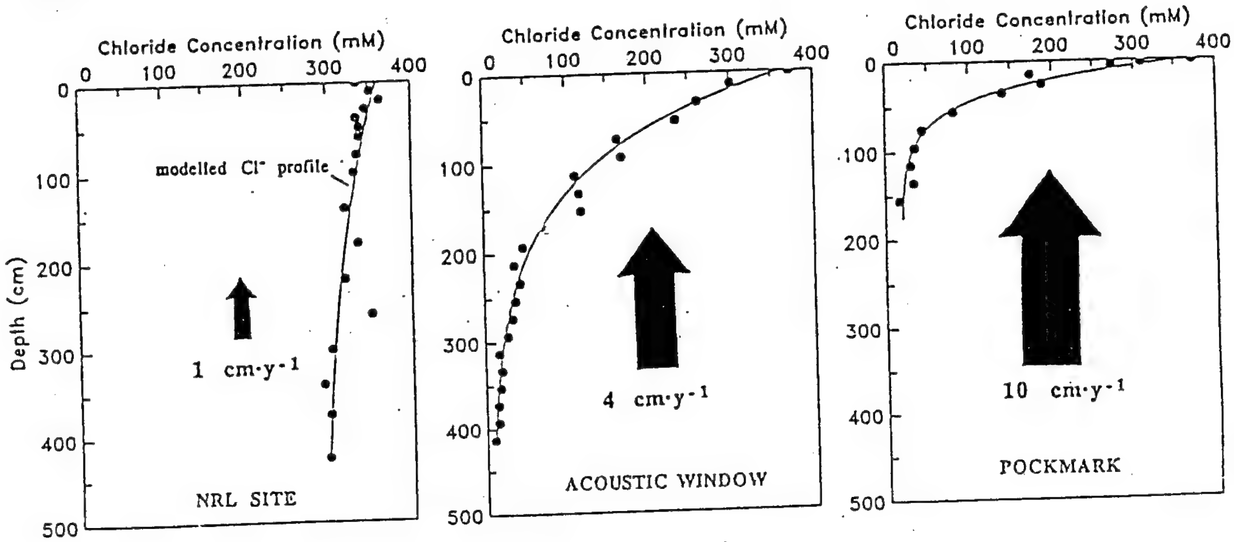
Figure 6. Overlay of salinity profiles from the three sites.

conditions the diffusion and advection terms are balanced with one another as shown in Figure 7. The calculated upward pore water velocities (v in the equation) which yield the best fit to the data are shown in the panels.

There is a ten-fold range in the advection rates between these sites from a low of 1 $cm \cdot y^{-1}$ at the NRL site to $10 \cdot y^{-1}$ at the pockmark. These rates are insignificant from the standpoint of their effect on the overlying water in the bay, but highly significant geochemically within the sediments. At the NRL site, where any effects of this flow are least significant, it is still possible that it is responsible for the drift of the concentrations away from the saturation line with depth below 1.5 m. Corroboration of this awaits further modelling that cannot be undertaken until all of the methane production rate data is in hand. At the window and the pockmark this flow is quite obviously responsible for the drop in methane concentrations with depth below maxima at 1-1.5 m depth, but it will also be interesting to model the methane profiles at these sites based on production rate data from the NRL site (the only place they were measured).

It is interesting to note that the methane concentrations reach saturation and lead to an acoustically turbid zone at both the NRL site, which has very little upward advection of pore water, and at the pockmark where advection is highest, but not at the window with its intermediate flow rate. This is the pattern also seen in some transects across individual pockmarks (e.g. the 1993 Eckernförde T-shirt picture from Doug Lambert's data) where the sediments outside the pockmark have a deeper gassy layer which abruptly changes to an acoustic window at the edge of the pockmark and then back again to a shallow gassy layer within the pockmark. This presumably is caused by the same transition in pore water flow rates from low to high. Full explanation of this phenomenon at our sites will have to await further modelling, but our tentative explanation is as follows.

CALCULATED VERTICAL ADVECTION RATES REQUIRED TO SUPPORT THE SUBSURFACE FRESHENING OF POREWATERS IN ECKERNFÖRDE BAY SEDIMENTS



$$\underbrace{\frac{d}{dx}\left(\varnothing\ D_s \frac{dc}{dx}\right)}_{\text{Diffusion}} = \underbrace{-\varnothing\ v \frac{dc}{dx}}_{\text{Advection}}$$

Figure 7. Chloride concentration profiles at the three Eckernförde Bay sites and the calculated vertical pore water advection rates required to maintain them in balance with the diffusive flux of chloride into the sediments from the overlying water. c=chloride concentration; x=distance below the sediment-water interface; ø=porosity; Ds=the whole sediment diffusion coefficient, v=porewater velocity.

At the acoustic window there is still a significant surficial layer of sediment in which sulfate reduction takes place. This is known because sulfate penetrates about 35 cm into the sediment (not shown) and it shows up as an upward concavity in the uppermost methane concentration data. Thus, the methanogenic bacterial community, as at the NRL site, does not have access to the freshest organic substrate. It has to first be buried below the depth of sulfate depletion. The continual upward stripping of methane produced in the most active methanogenic sediments just below the depth of sulfate depletion is enough of a loss to prevent it from reaching saturation.

At the pockmark, the 10 cm·y^{-1} upward flow, in combination with sulfate reduction in the surficial sediment, leads to sulfate depletion by 13 cm depth. The methanogenic community thus has access to much less highly degraded organic material than elsewhere because it is only about 1/3 as old. This leads to much higher total methane production at this site than at either the window or the NRL

site. The upward stripping of methane due to pore water advection is more than compensated for by the higher production rates due to access to fresh substrate.

WORK TO BE COMPLETED

We still have a large suite of samples to be worked on prior to output of our major publications from this work, including the following:

- Stable carbon and hydrogen isotopes of methane from the three sites
- Stable carbon isotopes of CO_2
- Organic carbon and nitrogen and total sufur analysis of the bulk sediments
- Stable carbon isotopes of the bulk sediments
- Methane production and oxidation rate samples
- Sulfate reduction rate samples

PAPERS PRESENTED AT NATIONAL AND INTERNATIONAL MEETINGS

Albert, D. B. and C. S. Martens. Biogeochemical processes in surficial sediments of Eckernförde Bay. 1994 AGU, ASLO Ocean Sciences Meeting, San Diego, CA

Martens, C. S. and D. B. Albert. Biogeochemical processes controlling gas production, consumption and transport in organic-rich marine sediments. 1994. Gassy Mud Workshop, Kiel, Germany.

Marten, C. S., D. B. Albert and G. B. Avery. Controls on the stable isotopic composition of methane in rapidly accumulating coastal sediments. 1994. Third International Conference on Gas in Marine Sediments, Texel, Netherlands

Martens, C. S., D. B. Albert, H. Fiedler and F. Abegg. Biogeochemical processes controlling gas bubble production and distribution in organic-rich sediments. 1994 Acoustic Society of America Meeting, Austin, TX

2.13 Physical and Biological Mechanisms Influencing the Development and Evolution of Sedimentary Structure (Principal Investigators: C.A. Nittrouer and G. R. Lopez)

CBBLSRP FY94 YEAR-END REPORT

Physical and Biological Mechanisms Influencing the Development and Evolution of Sedimentary Structure

Charles A. Nittrouer

Glenn R. Lopez

Marine Sciences Research Center
State University of New York
Stony Brook, NY 11794-5000

INTRODUCTION

Research work completed during this year included participation in the summer 1994 cruise of the *R/V Planet*, ongoing analysis of samples collected on cruises collected in 1993 and 1994, presentation of two talks at the AGU Ocean Sciences meeting, and submission of two papers to Geo-Marine Letters. This report presents current findings of our research on the sedimentology and benthic biology of Eckernfoerde Bay.

SEDIMENTOLOGY AND RADIOCHEMISTRY

Summary of work to date

Sedimentological studies were conducted in central Eckernfoerde Bay. Sediment is characterized by beds of clay-sized material, with slightly coarser laminations (~10% silt and sand). Excess ^{234}Th activity indicates that mixing is limited to the upper 5 mm of the seabed. Accumulation rates, measured by ^{210}Pb geochronology, range from 5 to over 10 mm yr^{-1}. The relatively high accumulation rates and absence of a significant mixed layer in the central bay allow fluctuations of sedimentological processes to be recorded in fine detail. Sediment-transport studies indicate that the laminated bedding is caused by alternating deposition of storm-suspended sediments from adjacent shallow-water areas and fair-weather supply of fine suspended material advected from the open Baltic.

X-radiography

X-radiographs of cores from the central basin of Eckernfoerde Bay show laminations in the upper 20-30 cm of the sea floor. The laminations are interbedded with thicker beds (several cm thick). Contacts between beds and laminations are diffuse. Laminations are generally more

absorptive of X-rays than the thicker beds (thus appearing dark in positive prints: Fig. 1), and may be laterally discontinuous and inclined from horizontal.

Microfabric

Two general types of microfabric were observed in cores from the central basin: pelletal fabrics (pellets > 10% of volume; percentages are approximate) and non-pelletal fabrics (pellets < 10% of volume). Of these, pelletal fabrics are by far the most common, and may be either matrix supported or pellet supported. Transitions from non-pelletal layers to overlying pelletal layers tend to be gradational, whereas contacts between non-pelletal and underlying pelletal layers are sharp (Fig. 2).

Pelletal fabrics tend to be anisotropic. Non-pelletal laminations sometimes display graded bedding (Fig. 2); other laminations may show no obvious grain-size variations between layers. In general, microstructural laminations correspond to laminations observed in X-radiographs, and pelletal fabrics in thin section are associated with thicker, homogenized beds seen in X-radiographs.

Grain-size distribution

Grain-size distributions tend to be polymodal, with the primary mode centered between 9.5 and 11.5 ϕ and a secondary mode, less than 10% by mass, centered between 3 and 6 ϕ (Fig. 3). Subtle coarsening in the median grain size of each mode is commonly associated with laminations observed in X-radiographs, and non-pelletal, graded bedding in microfabric (Fig. 3). The coarsening associated with these laminations is accompanied by a 2-4% increase in the mass percentage of particles in the 3-6 ϕ size range.

Radiochemistry

Sediment accumulation rates in the central basin determined by ^{210}Pb geochronology range from 3 to over 10 mm per year (Fig. 4). Excess ^{210}Pb is present in the seabed to depths of 30-40 cm (Fig 4). Excess ^{234}Th is restricted to the upper 5 mm of sediment, indicating that mixing is restricted to this thin veneer in the sea floor. No significant seasonal variability in sediment mixing depths was observed over winter, spring and summer cruises, although intensity may of mixing may change. Lateral variability of accumulation rates within the central basin was minimal.

Shallow penetration of sediment mixing results in the preservation of a detailed environmental record (cm-scale) in central-basin sediments. Long-term variations in ^{210}Pb profiles were observed in central-basin cores (Fig. 4), indicating historical shifts in either ^{210}Pb flux in coastal waters or changing sediment supply.

Sedimentary Event Layers

Once a sediment layer is deposited, it is then subject to modification by biological and physical mixing. In the absence of physical mixing, the degree of event-layer preservation in the historical sedimentary record is a function of the deposited-layer thickness, the sediment accumulation rate, and the depth and rate of biological mixing (Guinasso and Schink, 1975; Nittrouer and Sternberg, 1981; Wheatcroft, 1990, 1994). Events layers thicker than the mixed layer can be generated by unusual events (from large storms or floods), and can overwhelm the benthos, interrupting biological mixing (Wheatcroft, 1994). The physical record of such an event would be a bed or lamination with: a sharp lower boundary (resting on top of a bioturbated bed), a physically stratified lower layer, and a gradual increase upward in the intensity of bioturbation. This sequence has been widely recognized in coastal depositional environments (Frey and Howard, 1986; Leithold, 1989; Aigner and Reineck, 1982; Wheatcroft, 1994). The conceptual model is consistent with sedimentation in the central basin of Eckernfoerde Bay.

Depositional and Post-depositional Processes: Preserved Fabric

In order to assess the relationship between pulsed sediment deposition and rate of bioturbation, laminations were examined in thin section for evidence of progressive bioturbation with age. The laminations clearly preserved in thin sections (Fig. 2) have sharp lower contacts, and grade upwards into progressively more pelletized sediment. This trend indicates that degree of pelletization can be used as an estimate of bioturbation intensity following event-layer deposition, when the pellets under study are resistant to breakdown. The thicknesses of unburrowed sediment in event layers are on the order of 3-5 mm, comparable to progressively pelletized layers. Each preserved lamination must have been initially thicker than the sediment mixing depth in the central basin, otherwise the lower boundary would not have been preserved.

Excess ^{234}Th activities (Fig. 4) were used to estimate the biodiffusion coefficient D_b (~ 0.3 cm^2 yr^{-1}) in central basin sediments, using a solution to the steady-state advection/diffusion equation (Aller and Cochran, 1976),

$$D_b=\lambda(z/ln(C_0/C_z))^2$$

where λ is the ^{234}Th decay constant (10.5 yr^{-1}), z is depth in the seabed (cm), C_0 is excess activity at the surface (decays per minute per gram of sediment: dpm/g), and C_z is excess activity at depth z (dpm/g). The thin surface mixed layer resulted in only two subsamples containing excess ^{234}Th (Fig. 4). Because of the rapid mixing rates relative to accumulation rates, biological mixing is assumed to control the penetration of excess ^{234}Th into the seabed.

A method useful for assessing appropriate length and time scales of bioturbation is the decomposition of the biodiffusion coefficient into a mean step length and rest period (Wheatcroft

and others, 1990) using the form $D_b = \delta^2/2\Omega$, where δ is mean step length, and Ω is mean rest period (yr). Assuming a step length of 2 mm (a value appropriate to the benthic community, based on body length: G. Lopez, pers. commun.), the rest period is 24 days. To advect a 1 mm layer through the 5 mm mixed layer in less time than the rest period (and so preserve the layer) would require rapid deposition at rates equivalent to 7.5 cm yr^{-1}, one order of magnitude higher than the mean accumulation rates in the central basin (~7 mm yr^{-1}). Event layers exceeding the mixed-layer thickness satisfy these conditions.

Decadal-Scale Stratigraphic Record

Evidence of fluctuating accumulation rate is found on decadal scales, determined by ^{210}Pb geochronology (Fig. 4), as well as scales of single events, represented by non-pelletized laminations seen in thin sections (Fig. 2). Such fluctuations have been documented regionally (Balzer and others, 1986), and have been linked to winter-storm frequency and resultant resuspension and deposition (Khandriche et al, 1986). Shear velocities in the central basin have upper limits below critical erosion values (Friedrichs and Wright, in press), precluding significant physical sediment mixing. Biological mixing is seasonally intense, but is limited to depths (~5 mm) on the same order as annual accumulation rates (5-10 mm yr^{-1}). Thus, upper sediments of the central basin preserve a relatively high-resolution historical record (cm-scale) of sedimentary processes.

Conclusions

The sedimentary input to the central basin is controlled by pulsed supply of fine particles from both proximal and distal sources. Time-series benthic-boundary-layer observations (Friedrichs and Wright, in press) indicate physical sediment mixing to be insignificant. Biological mixing is intense, but presently limited to the upper 5 mm of seabed. Sediment pulses (storm layers) exceeding the mixed-layer thickness may be preserved as individual laminations. Slower deposition results in intensely reworked and pelletized sediment (pelletal fabric). Particle and chemical tracers reaching the seafloor may be vertically resolved to increments of ~5 mm, preserving a detailed stratigraphic record.

Fluctuations in the frequency of sediment pulses cause variations in ^{210}Pb accumulation rates (3-10 mm yr^{-1}). Similarly, sedimentary fabric (mm and cm scales) displays subtle gradients in grain size and bioturbation (including pelletization) that correlate to fluctuations in sediment supply rate.

BENTHIC BIOLOGY

Summary of work to date

The benthic macrofaunal community of Eckernfoerde Bay was characterized in terms of abundance and community structure. The community was dominated by small surface deposit-feeding animals. Faunal abundances in spring 1993 were 30,000-80,000 m^{-2}, and were 2,000-9,000 m^{-2} in summer 1994. Particle bioturbation was limited to the top 0.5-1.0 cm throughout Eckernfoerde Bay. Functional group classification, faunal abundances, organism size, and particle bioturbation are consistent with the hypothesis that the benthic community of Eckernfoerde Bay is controlled by a regular disturbance which maintains the community at a low level of complexity. All measured biological components are consistent with sedimentological and radiochemical studies which indicate a very thin layer (<1cm) of biological mixing.

Benthic Sampling

Benthic samples were taken during four ten-day cruises aboard the R.V. *Planet* and R.V. *Helmsand*, German naval research ships, during spring 1993 and summer 1994. Benthic sampling was focused around the acoustic tower deployment sites - Old Tower, New Tower - in the central basin (Fig. 5). Other samples were taken from the landward and seaward ends of the bay. These included both muddy sites - Eckernfoerde Navy Base, Stanic Tower, Hausgarten - and one sandy site, Mittelgrund. Three or more replicate box cores (20 x 30 x 50 cm) were collected per station. Three subcores were taken from each box core, were extruded, and sectioned into 0-2 and 2-10 cm sections. Animals were seived from sediment using a 500-μm sieve and preserved. Animals were identified to the lowest taxonomic group (usually species). Each taxonomic group was assigned to one of the following functional groups: surface deposit feeder, head-down deposit feeder, suspension feeder, or carnivore (see Table 1).

A bioturbation experiment was conducted to compare vertical particle mixing rates in different sediments and benthic communities. Three 15 cm diameter cores were collected from four stations along the axis of the bay - New Tower, Old Tower, Eckernfoerde Navy Base, Mittelgrund - in April 1993. Cores were maintained in a running seawater sytem at a shore lab. A 50 ml suspension of orange fluorescent particles (Radiant Pigment, 4-10 μm diameter, 1.4 sp. gravity) in seawater was added to the overlying water in each core, and allowed to settle onto the sediment surface for 24 hours. There was one control core and two experimental cores from each station. Nine to 12 subcores (10 ml syringe cores) were taken from each core. Subcores were vertically sectioned into 0-0.5, 0.5-1.0, 1.0-1.5, 1.5-2, 2-3, 3-4, and 4-5 cm intervals. Salinity and temperature were monitored during the course of the experiment. Experimental cores were incubated for approximately 2 weeks. Samples were analyzed for fluorescence of tracer particles

(modified from Carey 1989). All values were corrected for background fluorescence. Values from each depth interval were expressed as percent of the total fluorescence in that subcore.

Biological Observations

Macrofaunal abundance was high throughout the bay, dominated by small adults and juveniles of larger species. The dominant macrofauna consisted of 16 species (90% of total species) and 4 functional groups (Table 1). Benthic samples from the muddy stations - Old Tower, New Tower - in both 1993 and 1994 were dominated by small, numerous surface deposit feeders. The polychaete *Polydora ciliata* and the tellinid bivalve *Abra alba* accounted for 75-90% of all animals in many samples. Most of the *A. alba* were juveniles (<2.5 mm). Adult *Abra alba* were absent but their characteristic fecal pellets were abundant in the central basin; their presence indicates lateral transport from the sides of the basin. The surface deposit feeding cumacean, *Diastylus rathkei*, was numerically important in the June 1994 samples.

Abundances of surface deposit feeders in March-May, 1993 samples (27,000 - 73,000 m^{-2}) were significantly greater than the June-July, 1994 abundances (1,700 - 9,000 m^{-2}) (Fig. 5). Decreases in abundance were coupled with a shift in community composition at the muddy stations (Tower stations, Navy Base, Transect Station A, Hausgarten). The relative abundance of surface deposit feeders at the tower stations decreased from 80-90% in March-May 1993 to 60-85% in June 1994 (Fig. 6). Carnivores, especially *Harmathoe* sp. were proportionally more important in the June 1994 samples. The relative abundances of head-down deposit feeders remained unchanged between the two sampling years.

Mittelgrund is a sandy site near the mouth of Eckernfoerde Bay (see Fig. 5). This area supported a distinctly different fauna with significantly lower abundances than the muddy stations in the central basin. Mittelgrund had more head-down deposit feeders and a higher proportion of carnivores than the Tower sites (Fig. 6). Suspension feeders were also significantly more abundant in the sandier site.

The results of the particle mixing experiments showed that fluorescent particles were mixed approximately 0.5-1.0 cm into the sediment for all sites over a two week period (Fig. 7), regardless of functional group.

Our data indicates that the benthic fauna of Eckernfoerde Bay is dominated by small, surface deposit feeders, which do not mix particles deeply but probably mix the top cm of the sediment on short time scales (days). Differences in mean abundances between the two sampling years is thought to be seasonal (March-May in 1993 versus late June in 1994) and is consistent with previous work done in the Kiel Bight (e.g. Bosselman 1988, Meyer-Reil and others 1987, Rumohr and Arntz 1982).

The abundances and composition of benthic fauna in Kiel Bight is strongly linked to seasonal patterns of oxgen availability in the near-surface sediment (Kolmel 1979; 1977; Reimers; 1976). The benthic fauna of Kiel Bight typically experiences an exponential increase in abundance, dominated by small, tube-building polychaetes such as *Polydora ciliata*, from March to early June followed by a crash in June-July (Weigelt 1991; Bosselman 1988; Meyer-Reil and others 1987; Rumohr and Arntz 1982). In Eckernfoerde Bay, mean abundance of *P. ciliata* decreased an order of magnitude from the March-May 1993 sampling to the late June 1994 samples.

The primary controls on the benthic fauna of Eckernfoerde Bay during the study period were thought to be the rate of organic input to sediments, water column stratification, deep water mixing, and oxygen availability. During the spring bloom, carbon transport to the seafloor is between 10 and 15 g C m^{-2} and one-third of the yearly organic input can reach the seafloor of the Kiel Bight in 1-2 weeks (Meyer-Reil and others 1987). Portions of the Kiel Bight, particularly the southwest portion where Eckernfoerde Bay is located, are annually subjected to periods of hypoxia and anoxia in summer due to stratification of the water column and stagnant physical conditions (Weigelt 1991; 1990; Meyer-Reil and others 1987). We hypothesize that the low oxygen conditions that occur with water column stratification in Eckernfoerde Bay causes a regular disturbance which controls the complexity of benthic community structure.

All measured components of Eckernfoerde Bay - abundance, diversity, animal size, functional groups, particle mixing - point to a community dominated by pioneering species (sensu Rhoads and Boyer 1982), especially *Polydora ciliata* and *Capitella* sp., and a system controlled by a regular or recent disturbance which reduced the complexity of the community structure and sediment reworking by the benthic fauna. This is borne out by our bioturbation experiments (Fig. 7), our sedimentology and radiochemistry results, and with numerous German studies of the Kiel Bight (e.g. Weigelt 1991, Bosselman 1988, Meyer-Reil and others 1987, Rumohr and Arntz 1982).

REFERENCES

Aigner T and Reineck H-E (1982) Proximality trends in modern storm sands from the Helgoland Bight and their implications for basin analysis. Senckenbergiana Maritima 14: 183-215

Aller RC and Cochran JK (1976) ^{234}Th- ^{238}U disequilibrium and diagenetic time scales. Earth and Planetary Science Letters 29: 37-50

Balzer W,. Erlenkeuser H, Hartmann M, Muller PJ and Pollehne F (1986) Diagenesis and exchange process at the benthic boundary. In: Rumohr J, Walger E and Zeitschel B (Eds.), Lecture notes on coastal and estuarine studies, vol. 13: Seawater-sediment interactions in coastal waters. Berlin: Springer-Verlag, pp 111-161

Bosselman A (1988) Settlement and succession of benthic animals - a subtidal experiment in the German Bight compared with the "Benthosgarten" experiment in Kiel Bay. Kieler Meeresforsch., Sonderh., 6:375-388

Carey D (1989) Fluorometric detection of tracer particles used to study animal-particle dynamics. Limnol.Oceanogr., 34(3): 630-635.

Frey RW and Howard JD (1986) Mesotidal estuarine sequences: a perspective from the Georgia Bight. Journal of Sedimentary Petrology 56: 911-924

Friedrichs CT and Wright LD (in press) Resonant internal waves and their role in transport and accumulation of fine sediment in Eckernfoerde Bay, Baltic Sea. Continental Shelf Research

Guinasso NL and Schink DR (1975) Quantitative estimates of biological mixing rates in abyssal sediments. Journal of Geophysical Research 80: 3032-3043.

Khandriche A, Werner F and Erlenkeuser F (1986) Effects of easterly storms of winter 1978/79 on the sediments of the Eckernfoerder Bucht, western Baltic. Meyniana 38: 125-152

Kolmel R (1977) Okosysteme im Wechsel zur Anaerobiose. Zoobenthos und Abbau in zeitweise anoxischen Biotopen der Kieler Bucht.- Ph.D Thesis, Univ. Kiel and Rep. SFB 95 Univ. Kiel, 33, 403pp.

Kolmel R (1979) The annual cycle of macrozoobenthos: its community structures under the influence of oxygen deficiency in the Western Baltic, p.19-28, In: E. Naylor and R.G. Hartnoll (eds.), Cyclic Phenomena in Marine Plants and Animals, Pergamon Press, Frankfurt.

Leithold EL (1989) Depositional processes on an ancient and modern muddy shelf, northern California. Sedimentology 36: 179-202

Meyer-Reil L-A, Faubel A, Graf G, Thiel H (1987) Aspects of benthic community structure and metabolism,Ch. 3, p. 70-110. In: J. Rumohr, E. Walger, and B. Zeitzschel (eds.), Lecture Notes on Coastal and Estuarine Studies, Vol. 13, Seawater-Sediment Interactions in Coastal Waters.

Nittrouer CA and Sternberg RW (1981) The formation of sedimentary strata in an allochthonous shelf environment: the Washington continental shelf. Marine Geology 42: 201-232

Nittrouer CA, Sternberg RW, Carpenter R and Bennett JT (1979) The use of ^{210}Pb geochronology as a sedimentological tools: Application to the Washington continental shelf. Mar. Geol., 31, 297-316.

Reimers T (1976) Anoxische Lebensraume: Struktur und Entwicklung der Microbiozonose an der Grenzflache Meer/Meeresboden. Ph.D. Thesis and Rep. SFB 95 Univ. Kiel, 20, 134pp.

Rhoads D and Boyer L (1982) The effects of marine benthos on physical properties of sediments: a successional perspective, Ch.1, p. 3-52. In: P. McCall and J. Tevesz (eds.), Animal-Sediment Relationships: The Biogenic Alteration of Sediments, Plenum Press, New York, Vol. 2, Topics in Geobiology.

Rumohr H and Arntz W (1982) The "Benthosgarten" : a new approach for the study of soft-bottom communities. Meeresforsch., 29(4): 225-238.

Weigelt M (1990). Oxygen conditions in deepwater of Kiel Bay and the impact of inflowing salt-rich Kattegat-Water. Meeresforsch., 33:1-22.

Weigelt M (1991) Short- and long-term changes in the benthic community of the deeper parts of Kiel Bay (Western Baltic) due to oxygen depletion and eutrophication. *Meeresforschung*, 33:197-224.

Wheatcroft RA (1990) Preservation potential of sedimentary event layers. Geology 18: 843-845
Wheatcroft RA (1994) Spatial autocorrelation of mud-sand bed contacts in shelf environments. Eos 75: 203
Wheatcroft RA, Jumars PA, Smith CR and Nowell ARM (1990) A mechanistic view of the particulate biodiffusion coefficient: step lengths, rest periods, and transport directions. Journal of Marine Research 48: 177-207

PUBLICATIONS AND PRESENTATIONS TO DATE

Bentley SJ, Nittrouer CA and Sommerfield CA. Deveiopment of sedimentary strata in Eckernfoerde Bay, southwestern Baltic Sea. Submitted to Geo-Marine Letters
D'Andrea AF, Lopez GR and Craig NI. Benthic macrofauna and bioturbation in Eckernfoerde Bay, Southwestern Baltic Sea. Submitted to Geo-Marine Letters
Lopez GR, Craig NI, Wallace WG (1994). Benthic faunal distribution and sediment bioturbation in Eckernfoerde Bay. Eos 75: 180
Nittrouer CA, Sommerfield CK and Bentley SJ (1994). Formation of sedimentary strata in Eckernfoerde Bay. Eos 75: 180

TABLES AND FIGURES

Table 1. Rank order of dominant macrofauna in Eckernfoerde Bay.

Polydora ciliata	polychaete	surface deposit feeder/facultative suspension feeder
Abra alba	bivalve	surface deposit feeder/facultative suspension feeder
Diastylus rathkei	crustacean	surface deposit feeder
Capitella sp.	polychaete	small head-down deposit feeder
Heteromastus filiformis	polychaete	small head-down deposit feeder
Pectinaria koreni	polychaete	large head-down deposit feeder
tubificid sp.	oligochaete	large head-down deposit feeder
Scoloplos armiger	polychaete	large head-down deposit feeder
Anaitides maculata	polychaete	carnivore
syllid sp.	polychaete	carnivore
Nepthys sp.	polychaete	carnivore
Harmathoe sp.	polychaete	carnivore
Sigambra sp.	polychaete	carnivore?scavenger
Mytilus edulis	bivalve	epifaunal suspension feeder
Cerastoderma sp.	bivalve	infaunal suspension feeder
Corbula gibba	bivalve	infaunal suspension feeder

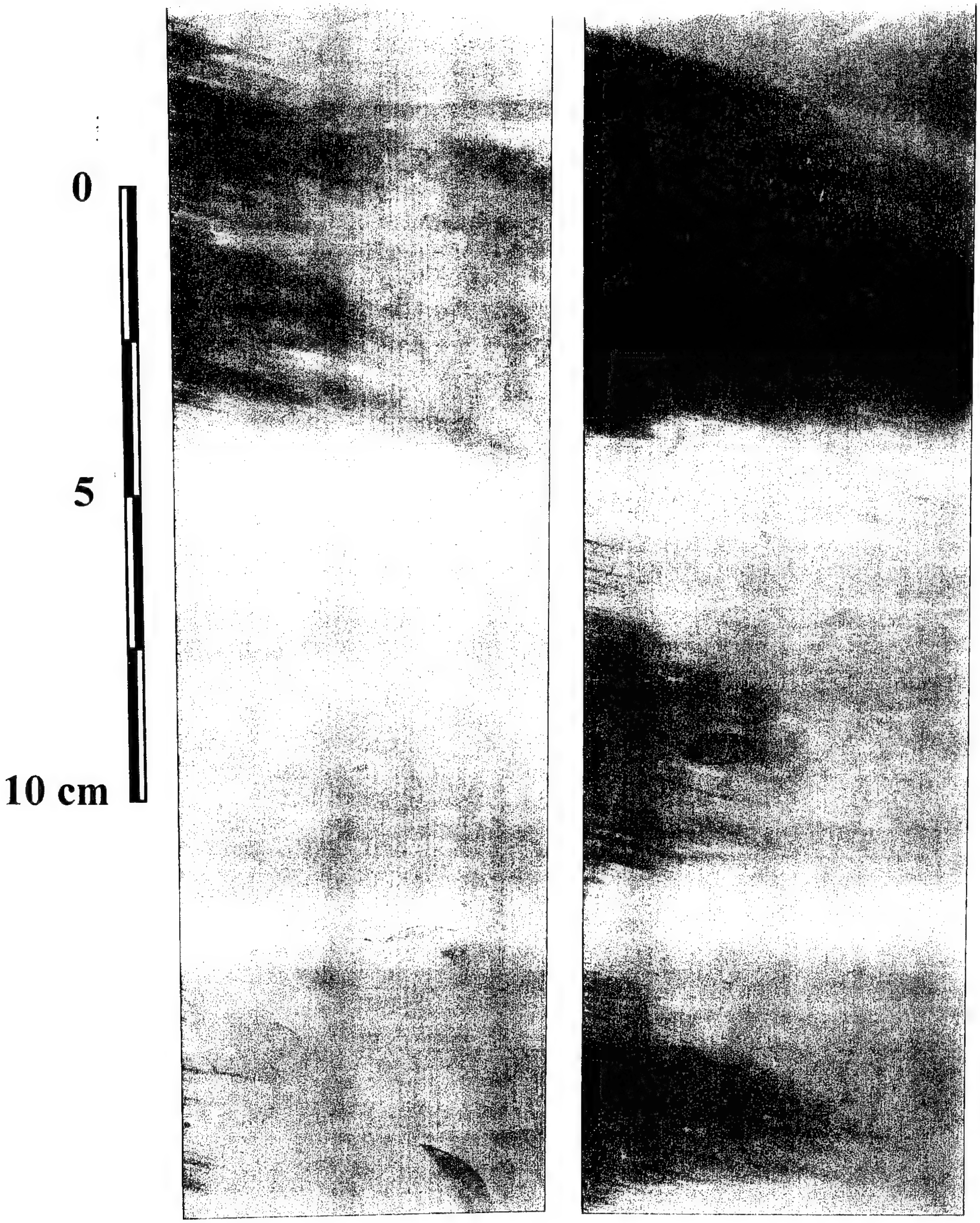
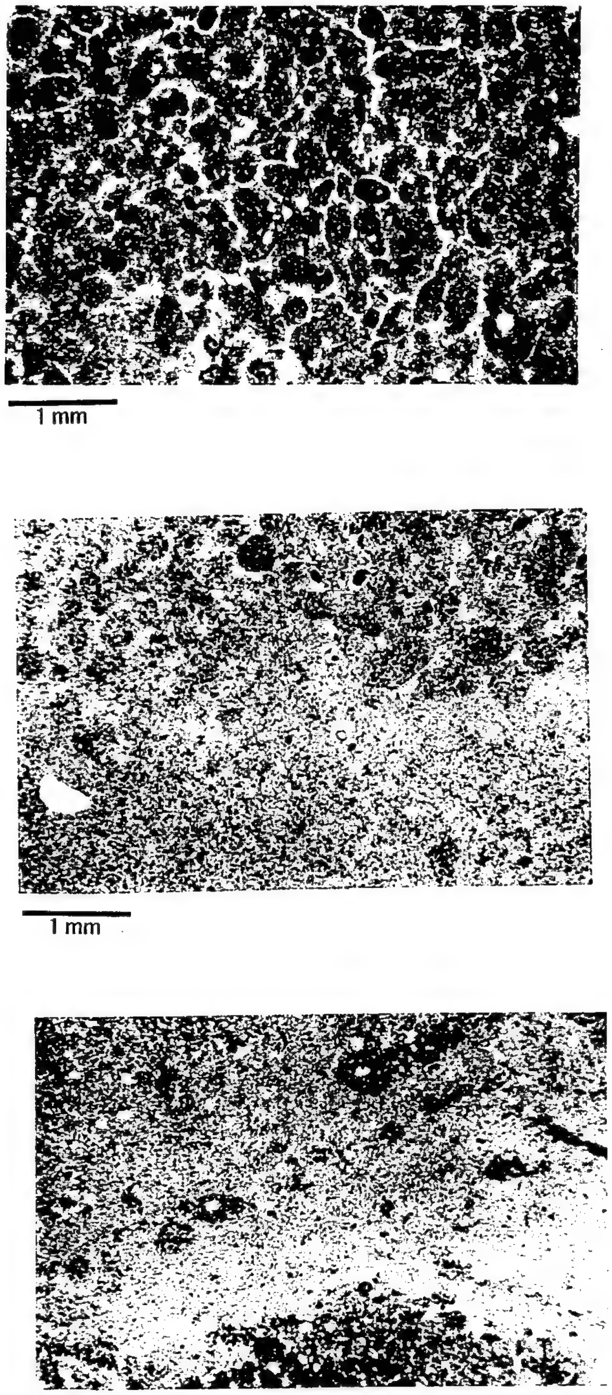


Fig. 1 X-radiograph positives, BS4-602 (Station N, Fig. 2) and BS4-611 (Station F, Fig. 2). Stations were separated by ~1 km. Note darker laminations (non-pelletized event layers). Thicker, light-shaded beds are intensely pelletized (see Fig. 2).

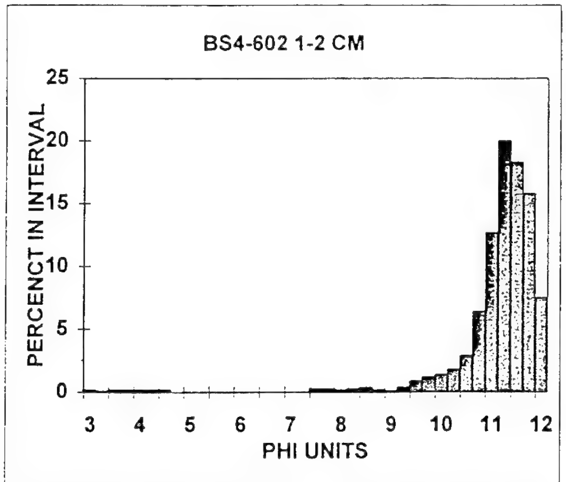


A

B

C

Fig. 2 Photomicrographs, BS4-602. Field of view is 5.5 mm wide. A) 2.5-2.8 cm depth, plane light: intensely pelletized horizon; fecal pellets produced by the surface-deposit-feeding bivalve *A. alba* B); 6.7-7.0 cm depth, crossed polars: upper portion of event layer showing transition from non-pelletized (lower) to pelletized fabric (upper); C) 7.0-7.3 cm depth, crossed polars: basal contact between non-pelletized event layer and underlying pelletized horizon.



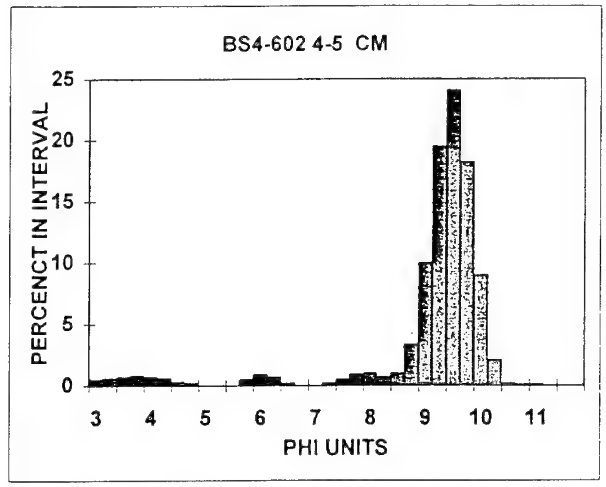
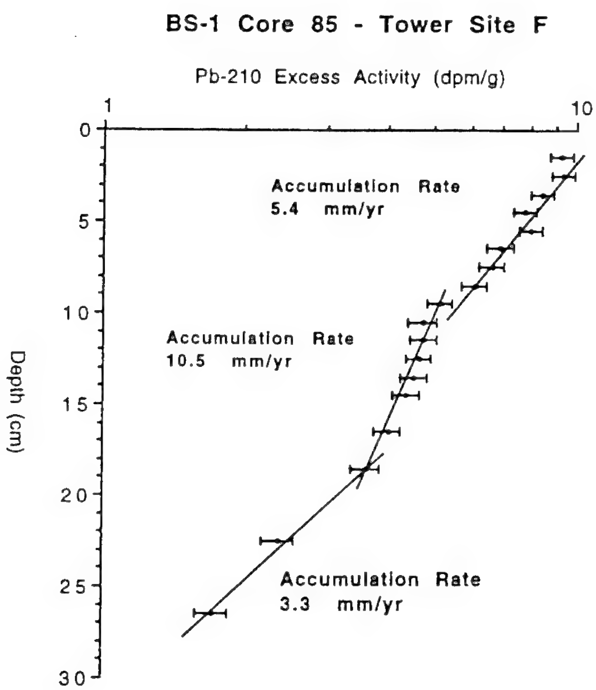


Fig. 3 Grain size distributions. A) BS4-602, 1-2 cm; B) BS4-602, 3-4 cm. The 1-2 cm interval is characteristic of pelletized intervals, and the 3-4 cm interval, slightly coarser, is characteristic of non-pelletized event layers.



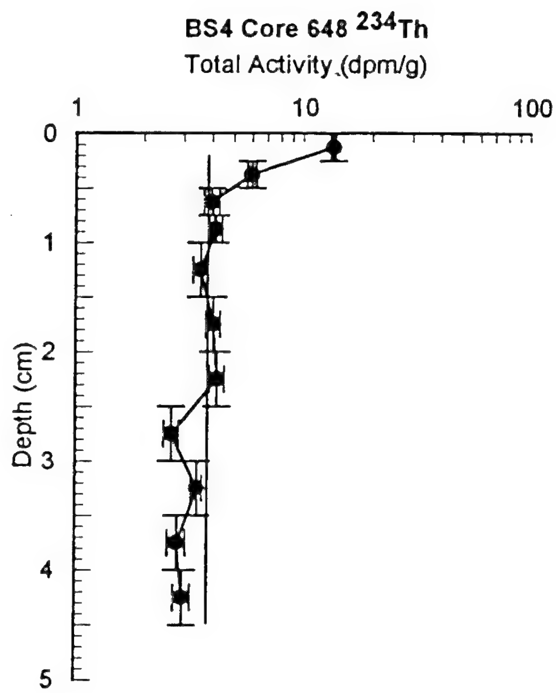


Fig. 4 Radiochemical profiles. A)Excess ^{210}Pb, BS1-85 (Station F, Fig. 2), note changes in accumulation rate through time; B) Total ^{234}Th, BS4-648, background levels are ~4 dpm/g and excess activities are restricted to the upper 5 mm.

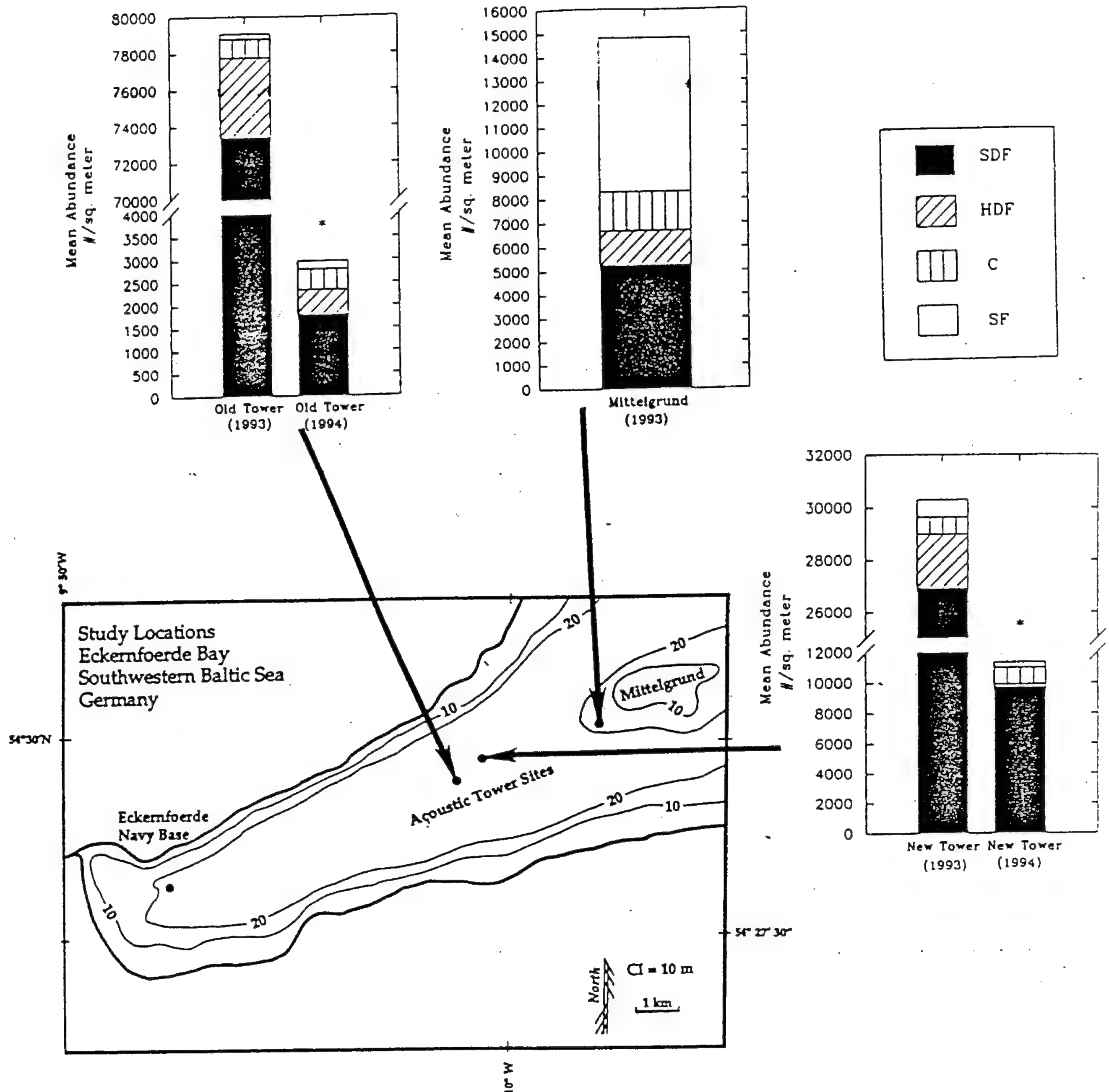


Figure 5. Mean Abundances at Primary Study Sites, 1993: mean from three cruises in Spring, 1993, 1994: mean from one cruise in Summer, 1994. SDF = surface deposit feeders; HDF = head-down deposit feeders; C = carnivores; SF = suspension feeders; B = browsers. * = significantly different abundances than 1993 samples (α=0.05).

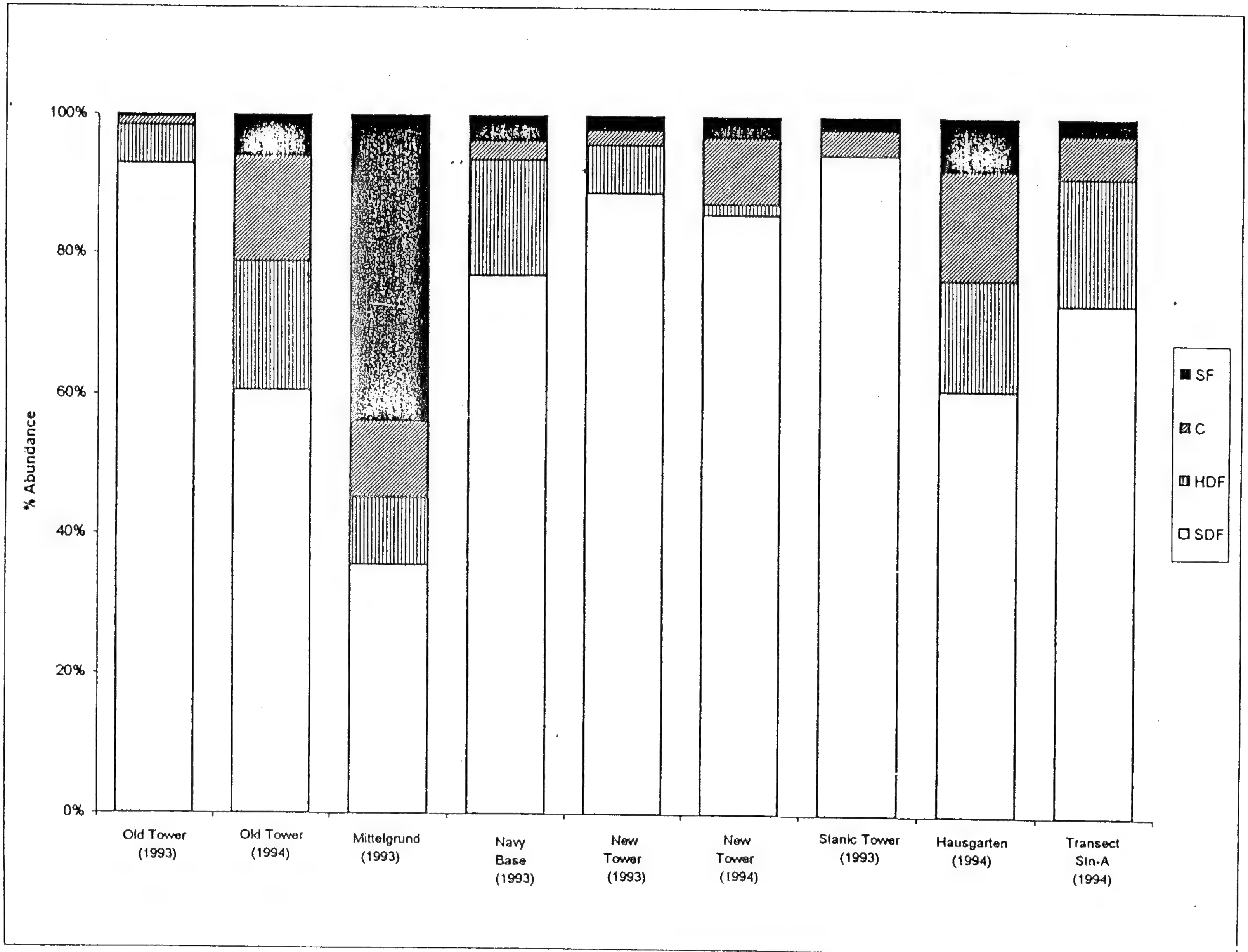


Figure 6. Percent Composition of Functional Groups by Station. SDF = surface deposit feeders; HDF = head-down deposit feeders; C = carnivores; SF = suspension feeders; B = browsers.

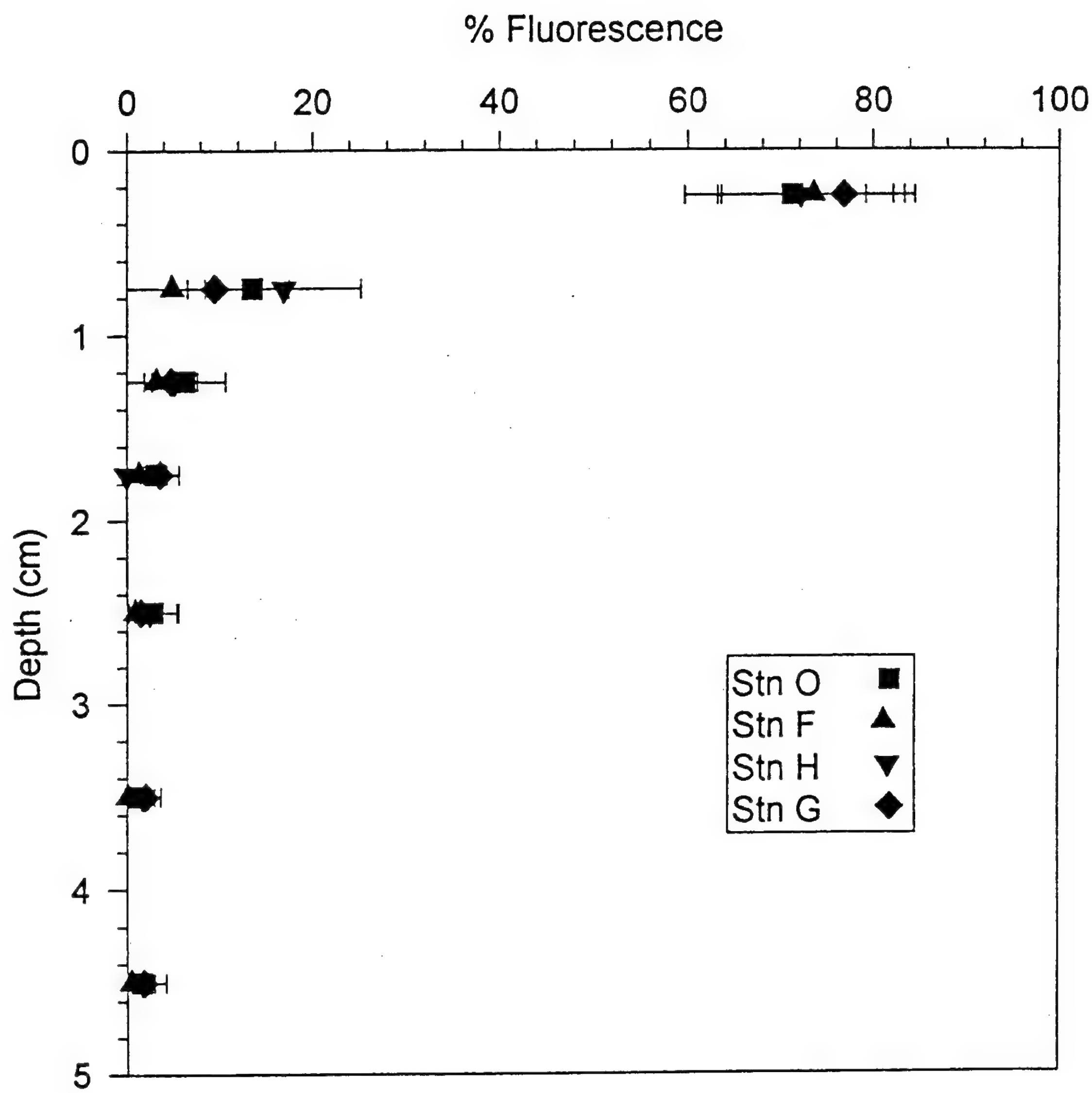


Figure 7. Vertical profiles of percent fluorescence (means and standard deviations) at primary study sites. Values are corrected for background fluorescence. Stations: O = New Tower, F = Old Tower, H = Eckernfoerde Navy Base, G = Mittelgrund.

2.14 Detection of Continuous Impedance Structures Using a Full Spectrum Sonar (Principal Investigator: S. Schock)

Final Report for CBBLSRP

Project Year: 1994

Project Title: Detection of Continuous Impedance Structures Using a Full Spectrum Sonar

Principle Investigator: Dr. Steven Schock
Center for Acoustics and Vibration
Dept of Ocean Engineering
Florida Atlantic University
Boca Raton, FL 33431

Date: 5 January 1995

Abstract

The FY 94 effort consisted of 1) an experiment in Kiel Bay during the period of 27 June 94 through 3 July 1994 to collect normal incidence reflection data over the range of 1 to 10 kHz and 2) post-processing of FM acoustic data for sediment classification and property analyses. The new data sets extended the lower end of the Kiel Bay data sets to 1 kHz and had reduced volume scattering due to the use of arrays with higher directivity. Sediment classification analyses demonstrated algorithms for predicting profiles of attenuation and impedance. The normalized standard deviation of the reflection coefficient was used to indentify areas with relatively high surface roughness.

Eckernfoerder Bucht Cruise Report for 6/27/94-7/3/94

An FM subbottom survey was conducted during the period of 27 June to 3 July 1994 on the WFS Planet. The purpose of the experiment is to collect normal incidence reflection data over the range of 1-10 kHz at core sites where the physical and acoustic properties of the seabed are known. The FM acoustic data and core data will be used to test new sediment classification techniques being developed under contract to ONR.

An X-Star subbottom profiler (currently manufactured by EG&G Marine Instruments) with an SB512 towed vehicle transmitted 20 msec long FM pulses over the frequency bands of 1-5, 1-6 and 2-10 kHz. The vehicle was usually towed at a depth of 6 meters and 12 meters off the starboard side of WFS Planet. The survey speed was usually 4 knots. Figure 1 shows the survey lines and core sites. Table 1 provides a summary of the line numbers, pulse characteristics, tape # and dates of data collection. All data was recorded in SEG-

Y format. Syledis navigation data was collected at intervals of 1 sec and recorded with each acoustic transmission. The transmission rate was usually 8 pulses per second. Table 2 provides a list of cores where acoustic data was collected (within 50 meters of a core site).

A summary of the events is:

23 June 94		FAU personel and equipment arrived
24 June 94		Setup and tested sonar and interfaced Syledis
27 June 94	1004	10 minute sea test
	2020	Pier calibration: Set calibration constants for each pulse to provide a 0dB air-water interface reflection
28 June 94	0136-0634	Data collection
	2030-2109	Pier calibration : Set calibration constants for each pulse to provide a 0 dB air-water interface reflection
29 June 94	0220-0710	Data collection
30 June 94	0241-0555	Data collection
1 July 94	0152-0722	Data collection
	2308-0600	Data collection
2 July 94	1710-2057	Pier side calibration check : Transmitted continously at full power to determine drift in calibration due to amplifier heating. Measured calibration offsets at fish depths of 4.5, 6 and 12 meters.
3 July 94	2227-2350	Data collection; secured due to failed underwater splice

Sediment Classification Analyses:

Impedance Inversion

An impedance inversion procedure developed under contract to ONR was used to predict impedance profiles using chirp sonar data collected in Kiel Bay. Impedance profiles are estimated by measuring the amplitude and phase of each subbottom reflection (including overlapping reflections) and calculating the interlayer reflection coefficients from which the impedance of each layer is determined iteratively starting at the sediment-water interface. These predicted vertical profiles of impedance were compared to impedance values calculated using measurements of velocity and bulk density made on cored sediments. Figure 2 shows an impedance profile calculated from the FM data sets, the corresponding impedance profile derived from core velocity and bulk density measurements, and the corresponding subbottom image. The drop in impedance estimated by the chirp sonar near the end of the profile in Figure2 suggests that a gassy layer causes the phase inversion and the predicted decrease in impedance.

Standard deviation of the Reflection Coeffcient

Ping to ping variability of the normal incidence reflection coefficient was studied using a data set acquired during the 1993 Panama City CBBL experiment. Large changes in the ping to ping variability of the echo strength can be seen in the contour map of the Panama City survey area shown in Figure 3. This map was generated by calculating the normalized standard deviation of the reflection coefficient every 50 acoustic returns. The normalized standard deviation of the reflection coefficient is higher in the southern section of the survey area suggesting that the the surface roughness is greater in that area. This results suggests that ping to ping variability can be used to map surface roughness of the seabed.

Attenuation Estimation

Changes in the acoustic attenuation coefficient can be estimated by measuring the decrease in the center frequency per unit travel time of a wideband acoustic pulse. Figure 4 shows measurements of the center frequency of the backscattered signal at various subbottom depths (echo arrival times). Note that the center frequency does not change significantly in gas or mud, but decreases rapidly in sand or till. The greater the rate of decrease, the larger the attenuation coefficient of the sediments. This phenomenon is due to the fact that that attenuation increases with frequency, causing the a higher frequency components of the signal to dissipate more rapidly. In general, attenuation is higher for larger grain materials.

TABLE ONE: Survey Lines

DATE	LINE NUMBERS	PULSE	TAPE
6/28/94	6,7,8	E: 20ms 2-10kHz	EB3
6/29/94	15,17,19	E: 20ms 2-10kHz	EB4
6/30/94	28	E: 20ms 2-10kHz	EB5
	29	C: 20ms 1-6kHz	EB5
	28	B: 20ms 1-5kHz	EB5
7/1/94	38	B: 20ms 1-5kHz	EB6
	40,42	B: 20ms 1-5kHz	EB7
	45,46,47	B: 20ms 1-5kHz	EB8
7/2/94	49,51,53,55,57	E: 20ms 2-10kHz	EB8
7/3/94	68	E: 20ms 2-10kHz	EB10

TABLE TWO: Chronology of Core Site Crossings (within 50 meters of the sonar's track)

CORE	LAT.	LONG.	OFFSET	TIME	TAPE	DATE
GU316	54°29.298' N	09°58.777' E	25 m	01:50:51	EB3	6/28/94
G607	54°29.382' N	09°59.001' E	50 m	01:52:40	EB3	6/28/94
GU308	54°29.572' N	10°00.113' E	25 m	02:01:51	EB3	6/28/94
GU307	54°29,570' N	10°00.117' E	20 m	02:01:55	EB3	6/28/94
GU306	54°29.563' N	10°00.123' E	4 m	02:01:58	EB3	6/28/94
GU305/ GU304	54°29.558 'N	10°00.143' E	12 m	02:02:10	EB3	6/28/94
GU326	54°30.900' N	10°06.913' E	30 m	03:02:13	EB3	6/28/94
T16	54°29.727' N	09°57.772' E	45 m	05:40:46	EB3	6/28/94
GU315	54°29.558' N	10°00.275' E	45 m	02:51:25	EB4	6/29/94
GU313	54°29.550' N	10°00.252' E	35 m	02:51:38	EB4	6/29/94
G31	54°29.497' N	10°00.178' E	40 m	02:52:08	EB4	6/29/94
GK322	54°29.423' N	09°59.690' E	0 m	02:56:16	EB4	6/29/94
T43	54°29.400' N	09°59.640' E	25 m	02:56:42	EB4	6/29/94
G25	54°29.400' N	09°58.563' E	10 m	03:05:59	EB4	6/29/94

CORE	LAT.		LONG.		OFFSET	TIME	TAPE	DATE
G17	54°29.672'	N	09°57.832'	E	1 m	03:29:30	EB4	6/29/94
G12	54°31.030'	N	10°02.285'	E	10 m	04:10:05	EB4	6/29/94
G8	54°32.317'	N	10°06.548'	E	25 m	04:51:19	EB4	6/29/94
GU309	54°29.615'	N	09°59.477'	E	37 m	06:47:38	EB4	6/29/94
GU311	54°29.612'	N	09°59.478'	E	40 m	06:47:38	EB4	6/29/94
GU312	54°29.610'	N	09°59.477'	E	45 m	06:47:39	EB4	6/29/94
GU310	54°29.608'	N	09°59.465'	E	46 m	06:47:49	EB4	6/29/94
GU320	54°29.507'	N	09°58.943'	E	28 m	06:52:24	EB4	6/29/94
GU319	54°29.527'	N	09°58.947'	E	6 m	06:52:33	EB4	6/29/94
GU317	54°29.537'	N	09°58.947'	E	25 m	06:52:33	EB4	6/29/94
GU318	54°29.540'	N	09°58.947'	E	30 m	06:52:33	EB4	6/29/94
G527	54°33.375'	N	10°09.225'	E	8 m	03:33:54	EB5	6/30/94
G626	54°33.340'	N	10°06.990'	E	33 m	03:51:48	EB5	6/30/94
G626	54°33.340'	N	10°06.990'	E	5 m	04:39:36	EB5	6/30/94
G628	54°33.325'	N	10°11.788'	E	30 m	05:18:04	EB5	6/30/94
GU323	54°30.027'	N	10°01.690'	E	50 m	01:58:38	EB6	7/1/94
D159	54°29.752'	N	10°00.208'	E	25 m	02:11:49	EB6	7/1/94
GU204-208 /D210/ GU217-219 /D221	54°29.743'	N	10°.00.205'	E	35 m	02:12:00	EB6	7/1/94
D175	54°29.742'	N	10°00.200'	E	32 m	02:12:01	EB6	7/1/94
D171	54°29.735'	N	10°00.190'	E	45 m	02:12:03	EB6	7/1/94
GU309	54°29.615'	N	09°59.477'	E	4 m	02:17:48	EB6	7/1/94
GU311	54°29.612'	N	09°59.478'	E	11 m	02:17:48	EB6	7/1/94
GU312	54°29.610'	N	09°59.477'	E	15 m	02:17:48	EB6	7/1/94
GU310	54°29.608'	N	09°59.465'	E	10 m	02:17:51	EB6	7/1/94
GU320	54°29.507'	N	09°58.943'	E	5 m	02:22:26	EB6	7/1/94
GU319	54°29.527'	N	09°58.947'	E	10 m	02:22:26	EB6	7/1/94
G49/D50	54°29.402'	N	09°59.968'	E	45 m	03:20:32	EB7	7/1/94
G28	54°29.538'	N	10°00.512'	E	3 m	03:25:04	EB7	7/1/94
G9	54°32.063'	N	10°05.525'	E	37 m	05:48:18	EB7	7/1/94
G11	54°31.302'	N	10°03.355'	E	20 m	06:14:57	EB7	7/1/94
G12	54°31.030'	N	10°02.285'	E	22 m	06:27:00	EB7	7/1/94
G14	54°30.317'	N	10°00.183'	E	21 m	06:52:53	EB7	7/1/94
G15	54°30.227'	N	09°59.583'	E	1 m	06:59:44	EB7	7/1/94
G47	54°30.017'	N	09°58.867'	E	4 m	07:08:09	EB7	7/1/94
G46	54°30.020'	N	09°58.867'	E	10 m	07:08:09	EB7	7/1/94
G17	54°29.672'	N	09°57.832'	E	9 m	07:20:38	EB7	7/1/94
GU327	54°30.902'	N	10°06.688'	E	0 m	00:25:12	EB8	7/2/94

CORE	LAT.		LONG.		OFFSET	TIME	TAPE	DATE
D180	54°29.672'	N	10°00.195'	E	12 m	01:12:39	EB8	7/2/94
GK300	54°29.668'	N	10°00.160'	E	25 m	01:12:57	EB8	7/2/94
GU301	54°29.673'	N	10°00.158'	E	34 m	01:12:57	EB8	7/2/94
GK303	54°29.662'	N	10°00.152'	E	20 m	01:13:00	EB8	7/2/94
GK302	54°29.667'	N	10°00.148'	E	30 m	01:13:03	EB8	7/2/94
G641	54°29.622'	N	10°00.138'	E	50 m	01:13:09	EB8	7/2/94
G647	54°29.583'	N	10°00.000'	E	50 m	01:14:08	EB8	7/2/94
G618	54°29.473'	N	09°59.012'	E	25 m	01:21:23	EB8	7/2/94
G20	54°29.275'	N	09°56.375'	E	27 m	01:47:11	EB8	7/2/94
G23	54°29.673'	N	09°52.408'	E	50 m	02:03:51	EB8	7/2/94
G29	54°30.000'	N	09°59.983'	E	25 m	02:13:59	EB8	7/2/94
D180	54°29.672'	N	10°00.195'	E	25 m	02:53:15	EB8	7/2/94
GK300	54°29.668'	N	10°00.160'	E	30 m	02:53:27	EB8	7/2/94
GU301	54°29.673'	N	10°00.158'	E	41 m	02:53:33	EB8	7/2/94
GK303	54°29.662'	N	10°00.152'	E	22 m	02:53:33	EB8	7/2/94
GK302	54°29.667'	N	10°00.148'	E	37 m	02:53:33	EB8	7/2/94
G641	54°29.622'	N	10°00.138'	E	48 m	02:53:39	EB8	7/2/94
GU321	54°29.533'	N	09°59.532'	E	20 m	02:58:06	EB8	7/2/94
G648	54°29.435'	N	09°59.233'	E	46 m	03:00:13	EB8	7/2/94
G614	54°29.418'	N	09°59.667'	E	8 m	03:01:56	EB8	7/2/94
G613	54°29.408'	N	09°58.998'	E	10 m	03:02:00	EB8	7/2/94
G606	54°29.426'	N	09°58.984'	E	30 m	03:02:02	EB8	7/2/94
G615	54°29.392'	N	09°58.955'	E	25 m	03:02:16	EB8	7/2/94
G24	54°29.483'	N	09°58.593'	E	35 m	03:43:12	EB8	7/2/94
GK328	54°29.885'	N	10°00.518'	E	0 m	03:57:16	EB8	7/2/94
G19	54°29.903'	N	10°00.602'	E	0 m	03:57:54	EB8	7/2/94
G649	54°29.928'	N	10°00.166'	E	35 m	03:57:54	EB8	7/2/94
GK324	54°30.028'	N	10°01.083'	E	45 m	04:01:28	EB8	7/2/94
G18	54°30.027'	N	10°01.193'	E	5 m	04:02:17	EB8	7/2/94
GU315	54°29.558'	N	10°00.275'	E	30 m	04:38:45	EB8	7/2/94
GU313	54°29.550'	N	10°00.252'	E	35 m	04:38:57	EB8	7/2/94
GU304/ GK305	54°29.558'	N	10°00.143'	E	25 m	04:39:45	EB8	7/2/94
GU306	54°29.563'	N	10°00.123'	E	42 m	04:39:57	EB8	7/2/94
GU316	54°29.298'	N	09°58.777'	E	30 m	04:49:49	EB8	7/2/94
G618	54°29.473'	N	09°59.012'	E	20 m	05:36:14	EB8	7/2/94
G616	54°29.702'	N	10°00.167'	E	30 m	05:44:52	EB8	7/2/94
GK193	54°29.713'	N	10°00.183'	E	15 m	05:44:58	EB8	7/2/94
D196	54°29.728'	N	10°00.185'	E	12 m	05:44:58	EB8	7/2/94
D167	54°29.725'	N	10°00.190'	E	5 m	05:45:00	EB8	7/2/94
D171	54°29.735'	N	10°00.190'	E	22 m	05:45:00	EB8	7/2/94

CORE	LAT.		LONG.		OFFSET	TIME	TAPE	DATE
D179	54°29.732'	N	10°00.195'	E	18 m	05:45:04	EB8	7/2/94
D195	54°29.710'	N	10°00.200'	E	27 m	05:45:06	EB8	7/2/94
D175	54°29.742'	N	10°00.200'	E	30 m	05:45:06	EB8	7/2/94
GU204-208 /D210/ GU217-219 /D221	54°29.743'	N	10°.00.205'	E	30 m	05:45:10	EB8	7/2/94
D159	54°29.752'	N	10°00.208'	E	48 m	05:45:10	EB8	7/2/94
GU323	54°30.027'	N	10°01.083'	E	0 m	05:56:28	EB8	7/2/94
G24	54°29.483'	N	09°58.593'	E	50 m	22:27:11	EB10	7/3/94
GU318	54°29.540'	N	09°58.947'	E	40 m	22:30:14	EB10	7/3/94
GU317	54°29.537'	N	09°58.947'	E	45 m	22:30:14	EB10	7/3/94
GU310	54°29.608'	N	09°59.465'	E	15 m	22:34:37	EB10	7/3/94
GU312	54°29.610'	N	09°59.477'	E	16 m	22:34:43	EB10	7/3/94
GU309	54°29.615'	N	09°59.477'	E	25 m	22:34:43	EB10	7/3/94
GU311	54°29.612'	N	09°59.478'	E	20 m	22:34:44	EB10	7/3/94
GK193	54°29.713'	N	10°00.183'	E	20 m	22:40:48	EB10	7/3/94
D196	54°29.728'	N	10°00.185'	E	7 m	22:40:48	EB10	7/3/94
D167	54°29.725'	N	10°00.190'	E	0 m	22:40:52	EB10	7/3/94
D171	54°29.735'	N	10°00.190'	E	16 m	22:40:52	EB10	7/3/94
D179	54°29.732'	N	10°00.195'	E	10 m	22:40:55	EB10	7/3/94
D175	54°29.710'	N	10°00.200'	E	27 m	22:41:00	EB10	7/3/94
D195	54°29.742'	N	10°00.200'	E	31 m	22:41:00	EB10	7/3/94
GU204-208 /D210/ GU217-219 /D221	54°29.743'	N	10°.00.205'	E	36 m	22:41:01	EB10	7/3/94
D159	54°29.752'	N	10°00.208'	E	42 m	22:41:04	EB10	7/3/94
GU315	54°29.558'	N	10°00.275'	E	24 m	22:51:44	EB10	7/3/94
GU313	54°29.550'	N	10°00.252'	E	17 m	22:51:57	EB10	7/3/94

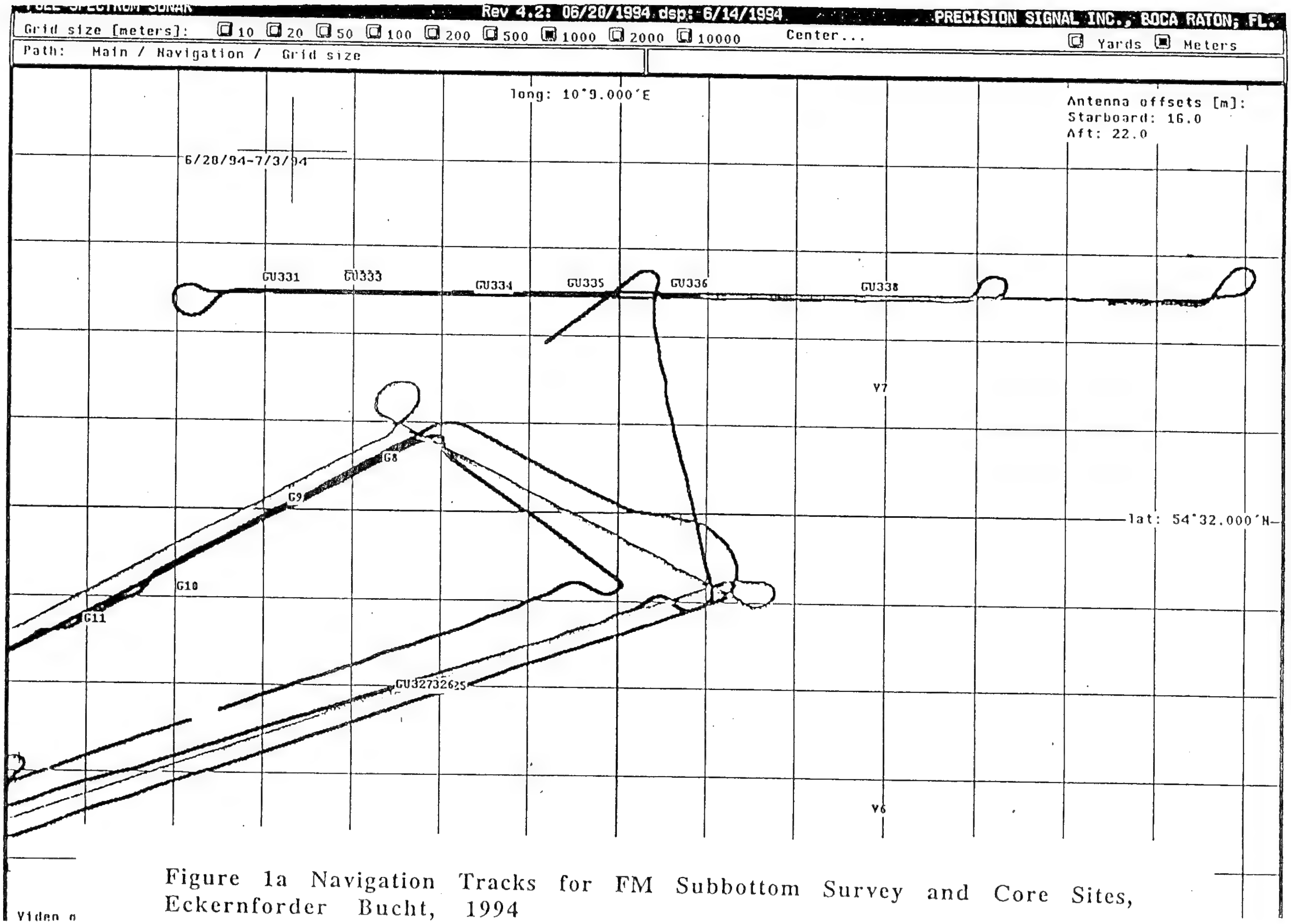


Figure 1a Navigation Tracks for FM Subbottom Survey and Core Sites, Eckernforder Bucht, 1994

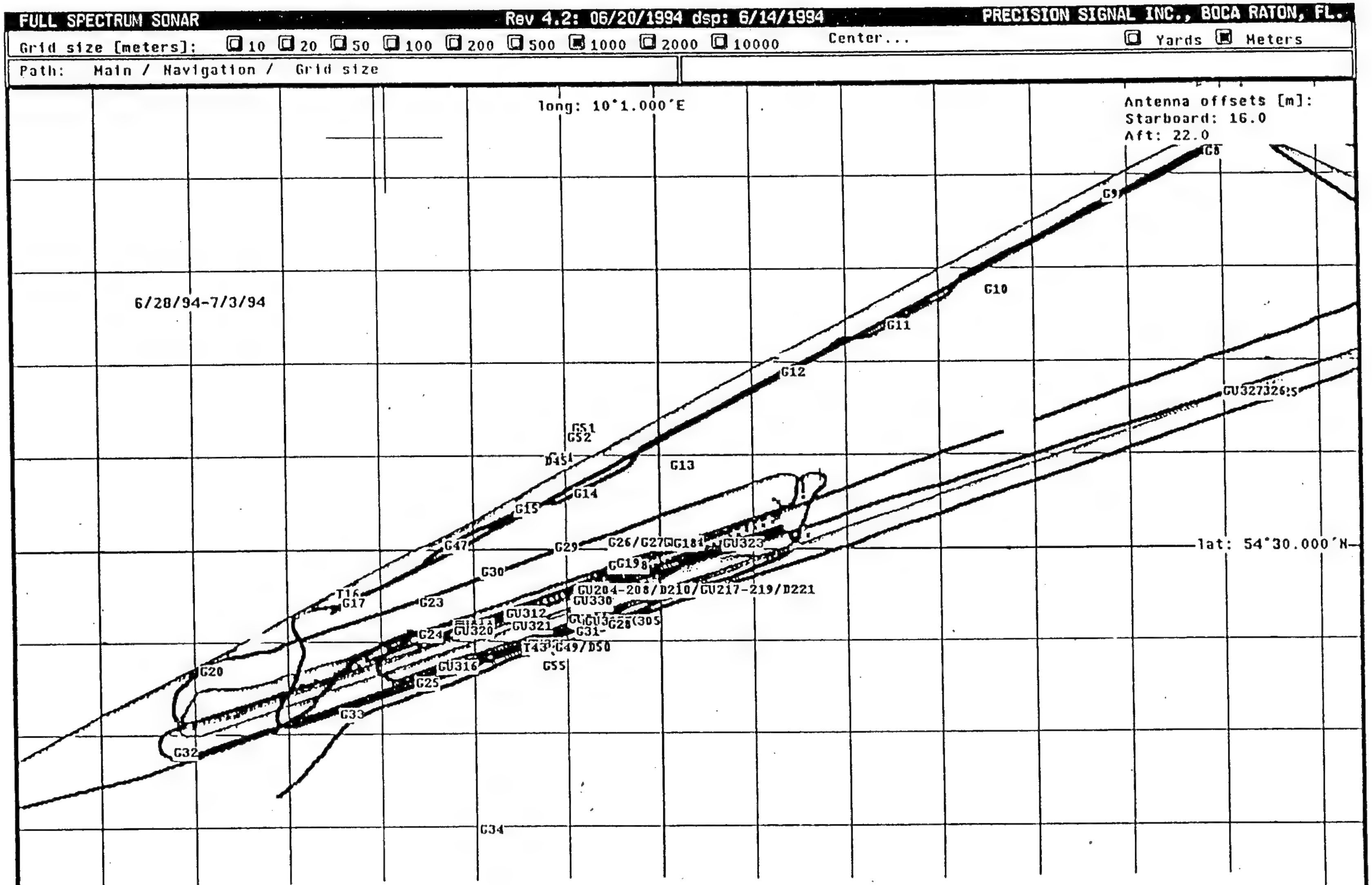


Figure 1b Navigation Tracks for FM Subbottom Survey and Core Sites, Eckernforder Bucht, 1994

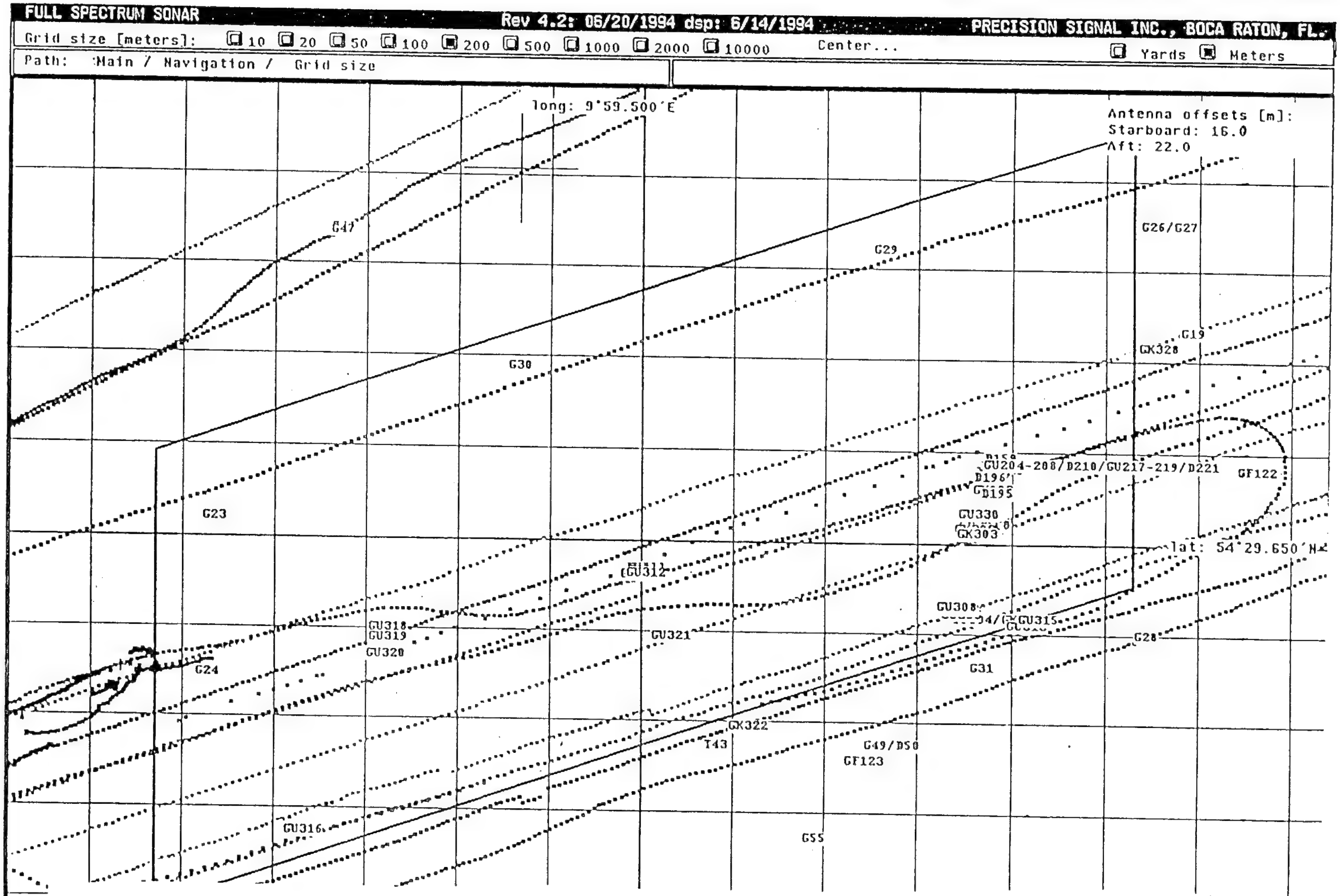


Figure 1c Navigation Tracks for FM Subbottom Survey and Core Sites, Eckernforder Bucht, 1994

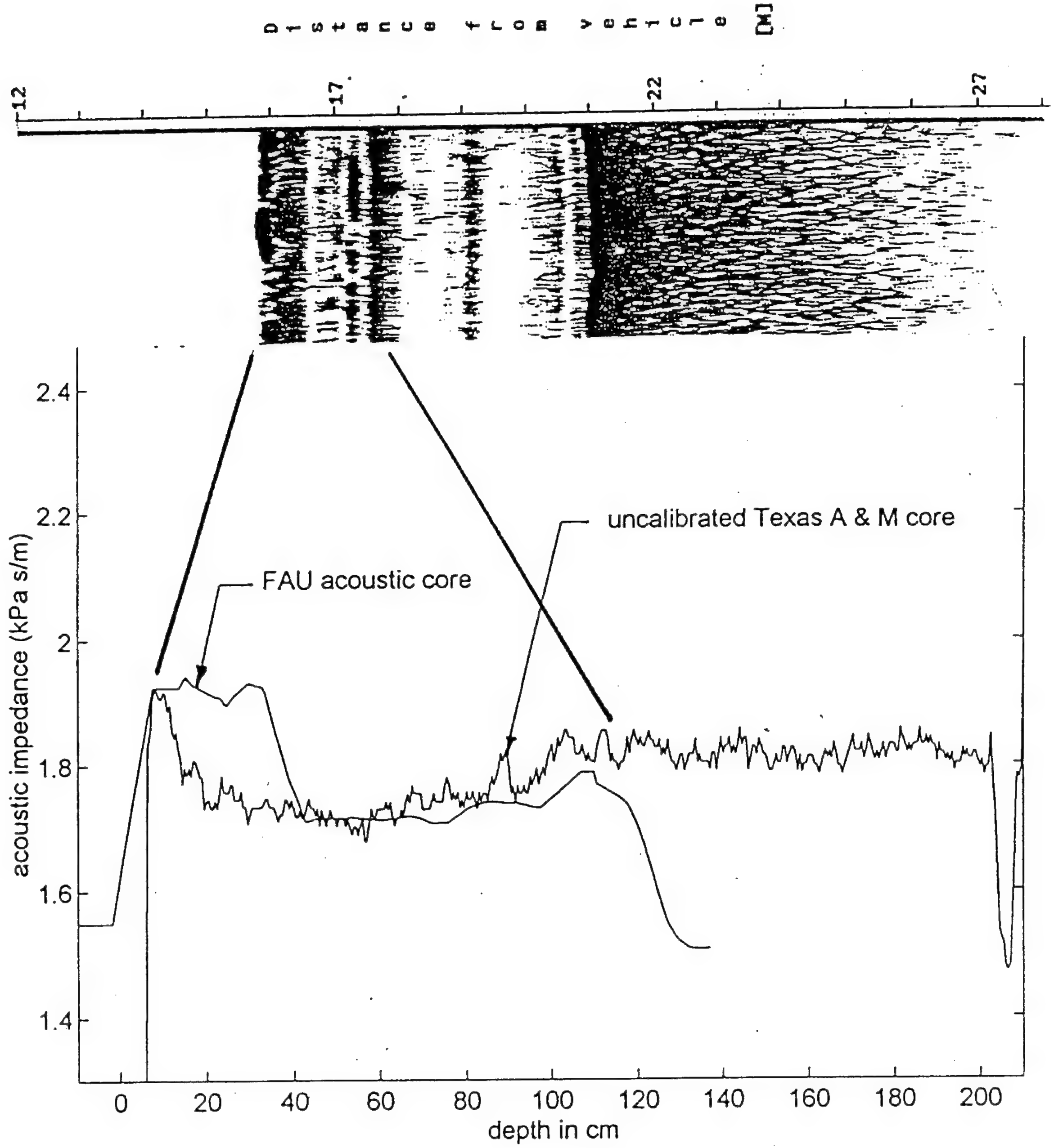


Figure 2 Comparison of vertical impedance profiles derived from A) 2-10 kHz normal incidence reflection data and B) measurements of compressional wave velocity and bulk density (provided by Texas A&M) made on a sediment core within 50 meters of the acoustic measurement.

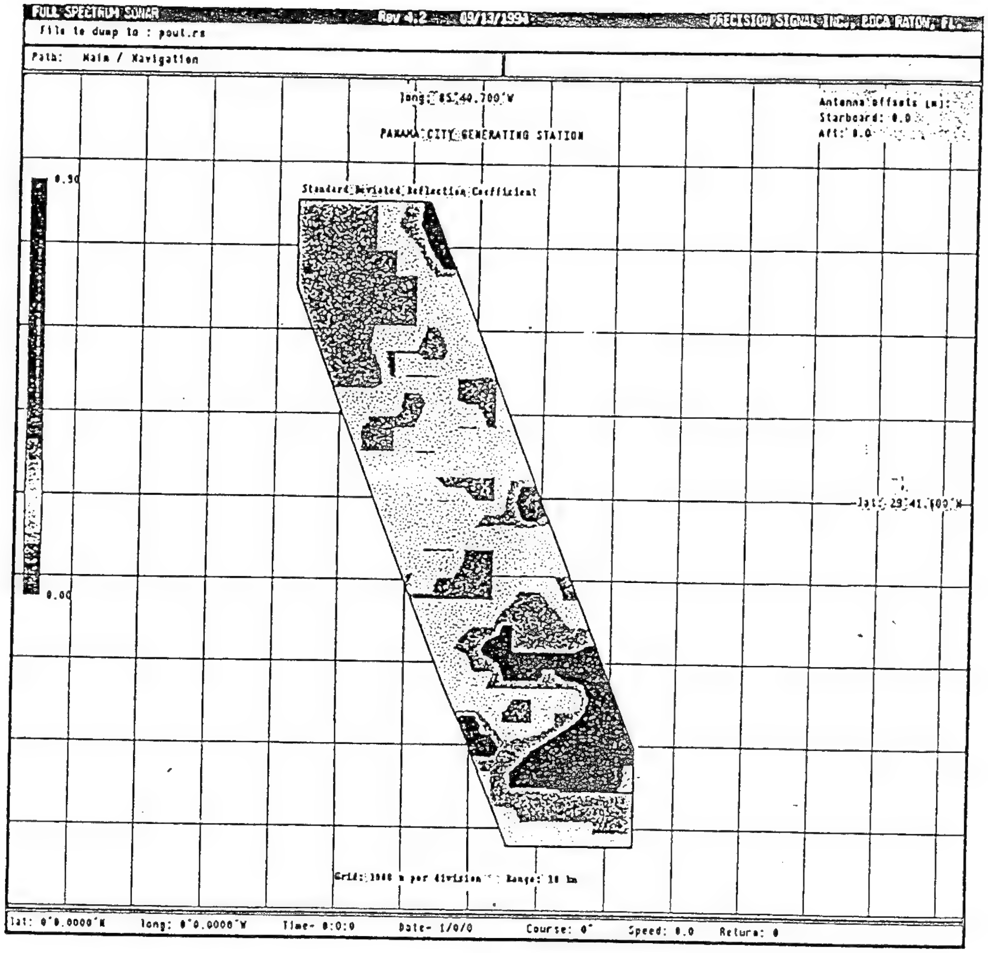


Figure 3 Contour map of the normalized standard deviation of the reflection coefficient measured with a FM subottom profiler using a 20 msec 2-10 kHz FM pulse. The survey was conducted during the 1993 CBBL experiment off Panama City, Florida.

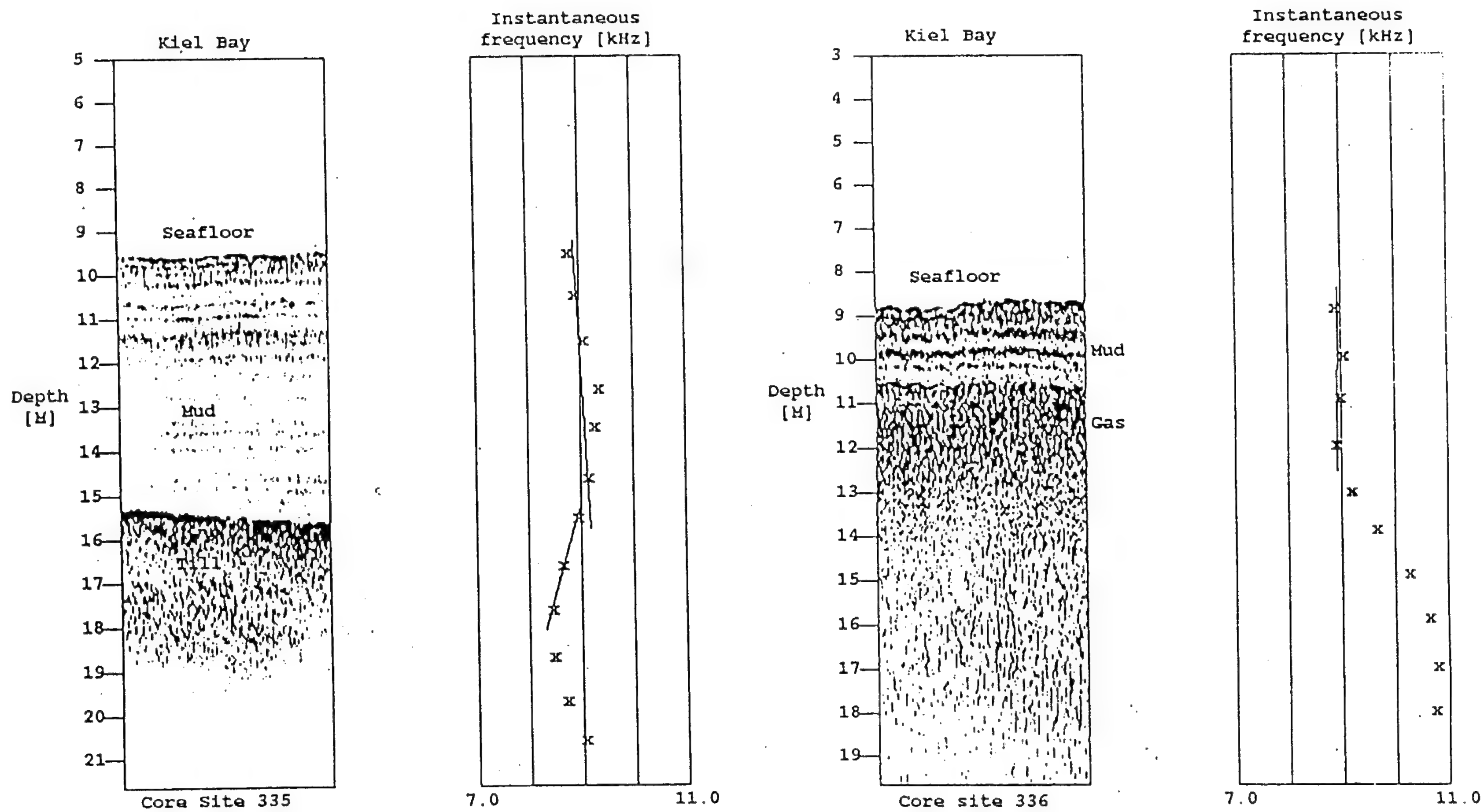


Figure 4 Vertical profiles of the center frequency of the backscattered acoustic energy (a measure of attenuation). The profile was generated using a 20 msec 2-15 kHz FM pulse transmitted and received at normal incidence to the seafloor.

2.15 Variability of Seabed Sediment Microstructure and Stress-Strain Behavior in Relation to Acoustic Characteristics (Principal Investigators: A.J. Silva, M.H. Sadd, G.E. Veyera and H.G. Brandes)

Variability of Seabed Sediment Microstructure and Stress-Strain Behavior in Relation to Acoustic Characteristics

CBBL/SRP FY94 YEAR-END REPORT

by

Armand J. Silva, Martin H. Sadd, George E. Veyera and Horst G. Brandes

Marine Geomechanics Laboratory
University of Rhode Island
Narragansett, RI 02882

Introduction

This is the second annual report, covering activities during FY 94 of the University of Rhode Island (URI), Marine Geomechanics Laboratory (MGL) research program as part of the Coastal Benthic Boundary Layer (CBBL)/Special Research Project (SRP). The overall objectives and progress of the program are described elsewhere. The focus of the URI program is on the variability of sediment geotechnical properties and microstructure with particular attention on stress-strain behavior and constitutive modeling in relation to geoacoustic characteristics. This report summarizes activities and results during FY 94, i.e. from October, 1993 through September, 1994. A more detailed report is available from either A.J. Silva at URI or M. Richardson at the Naval Research Laboratory, Stennis Space Center, MS 39529-5004. It is noted that the results described here will be combined with those in our first annual (FY 93) report, "Variability of Seabed Sediment Microstructure and Stress-Strain Behavior in Relation to Acoustic Characteristics," A.J. Silva, M.H. Sadd, G.E. Veyera, and H.G. Brandes.

This second year has been a very busy and productive one for the URI/MGL research team. The laboratory testing program for the Baltic Sea sediments has seen very significant progress; three papers on sediment characterization and geotechnical properties were presented at the Ocean Sciences meeting in San Diego, several manuscripts are in preparation, and a thesis is in the final stages of preparation. The microstructural constitutive modeling effort has advanced significantly; a presentation was made at the Ocean Sciences meeting, a paper has been published, and a thesis is in preparation. Several important improvements/additions have been made to the laboratory facilities and procedures. We have begun work on the Panama City, FL cores obtained in August, 1993. Finally, we participated in the Summer, 1994 Eckernförde cruise and have begun testing the recovered sediment samples.

Facilities

Over the course of the last year, we have continued to refine equipment and testing procedures based on experience with sediments obtained from two NRL experimental sites. The modifications and improvements to our systems are summarized below.

Constant Rate of Deformation (CRD) Consolidation Testing System: The flow pump units on our CRD systems have been outfitted with new redesigned smaller bore actuators to provide very low flow rates for CRD consolidation testing and permeability measurements. This improvement has extended our testing capabilities for evaluating the very soft Baltic Sea sediments. We can now test sediments ranging from very fine clay size up to fine sand size.

Triaxial Compression Testing System: Improvements have included the installation of new electronic sensors for measuring load and displacement, and the development of specialized preparation and testing procedures for the very soft Baltic Sea sediments. In addition, we are also preparing our system to test the granular materials from the Panama City, FL site and the upcoming Florida Keys experiment.

Geoacoustic Triaxial Compression Testing System: The various components of the acoustic system for measuring both compressional and shear waves in triaxial specimens are being installed in our triaxial cell by NRL. Supporting equipment (wave form generator, signal conditioner, cabling, etc.) has been ordered and should be delivered in November, 1994. There have been significant delays in procuring the acoustic system and we now anticipate that the geoacoustic triaxial system will be fully operational by early spring, 1995.

Multi-Sensor Core Logger (MSCL): All cores returned to the URI/MGL from the NRL experimental sites are analyzed using the MSCL to determine fine-scale profiles of density, compressional wave propagation velocity and attenuation. We are currently developing testing techniques and equipment for measuring the geoacoustic response of reconstituted/remolded sediments in the MSCL without the core liner. This approach will provide important information about the role of microstructure in sediments prepared under controlled environments, compared with those naturally developed in situ. Preliminary results are very encouraging. Additionally, the data obtained with the MSCL experiments will be compared with that from the geoacoustic triaxial system where stress state and loading conditions can be carefully controlled.

Personnel

During FY 94, the MGL research personnel working on the project included: a) Principal Investigator and Project Director, A.J. Silva (Ocean Engineering); b) three Co-P.I.'s, M.H. Sadd (Mechanical Engineering), G.E. Veyera (Civil Engineering), and H.G. Brandes (Ocean Engineering), c) four graduate students; A. Ag, D. Brogan, A. Gautam, and P. Pizzimenti (joined in 8/94); d) three part-time undergraduate students, e) a part-time administrative assistant, and f) various other technical support staff.

Research Cruise

One person from URI/MGL, H.G. Brandes, participated in the 1994 Eckernförde cruise aboard the R/V PLANET (June 27 through July 6). The main objectives of the URI/MGL involvement were to: a) obtain undisturbed sediments from selected gravity cores and box cores collected in and around the main experiment site, and b) make geotechnical measurements and observations of diver-collected cores under in situ pressures (in a hyperbaric chamber) and at atmospheric pressure.

Three large box cores (BS-BC-610, -659, and -678) were subsampled to provide undisturbed 5.08 cm diameter specimens for laboratory testing. Eleven triaxial, thirteen consolidation/permeability, and three 7.62 cm diameter Shelby tubes were collected, as well as numerous water content/bulk density samples. Two gravity cores, each over 4 m long were processed onboard to obtain undisturbed subsamples for laboratory testing (BS-GC-618), and to determine the shear strength profile at the study site (BS-GC-641). Water content/bulk density and bulk samples were also collected from the cores.

Strength measurements were taken in four diver-collected gravity cores that were stored in special pressurized containers to maintain in situ hydrostatic conditions. After CAT-scanning, the cores were transferred to the hyperbaric chamber where the shear strength was measured at a pressure equivalent to 26 m water depth, and later at sea level pressure conditions. Water content and bulk samples were also collected from the cores.

A preliminary review of the shear strength data indicates there is some loss of strength in the gassy sediments when the material was brought from in situ hydrostatic stresses to sea level conditions and allowed to de-gas. The amount of strength loss varied in each core and is probably due to: core handling, type of pressure chamber processing, and the extent to which the sediment was allowed to de-gas once it was depressurized. The shear strength data are being analyzed and results will be available in the near future.

Geotechnical Laboratory Experimental Program

The laboratory testing program is oriented toward an investigation of geotechnical properties, geoacoustic characteristics, and the relationships between them for sediments of interest to the program. Samples have been obtained from the Baltic Sea and Panama City, FL sites. Although testing to date has centered on Baltic Sea sediments, we have begun processing the available gravity cores from the Panama City cruise and are beginning triaxial, consolidation and permeability testing.

The laboratory program for Baltic Sea sediments is centered on triaxial stress-strain/strength, consolidation/permeability and index properties testing. During FY94 we conducted ten additional consolidation/permeability tests (Table 1). These test results will be combined with those presented in our first annual (FY 93) report ("Variability of Seabed Sediment Microstructure and Stress-Strain Behavior in Relation to Acoustic Characteristics", A.J. Silva, M.H. Sadd, G. E. Veyera, and H.G. Brandes) for analysis.

Compression indices range between 2.0 and 4.1, initial void ratios between 5.5 and 7.3, and overconsolidation ratios between 1.3 and 4.4. In situ permeabilities range between 9.8×10^{-7} and 3.2×10^{-4} cm/s. These results fall in line with our previous findings that characterize Baltic Sea sediments as having very high void ratios, large compressibilities, low to moderate permeabilities, and overconsolidation that decreases with depth. We have now completed most of the consolidation, permeability and index properties testing of the Baltic Sea sediments. The findings will be presented in a M.S. thesis, upcoming papers in Geo-Marine Letters and elsewhere.

Triaxial testing of Baltic Sea samples was conducted to determine their stress-strain and strength characteristics. It is extremely difficult to set up samples of this very soft material (porosity close to 90%) in a triaxial cell. Therefore, it was necessary to develop special methods and procedures to conduct these tests. Three Consolidated Isotropically Undrained (CIU) strength tests were conducted during this past year (Table 2). Deviatoric stresses at failure are extremely small and axial strains at failure are typically around 3%. The angle of internal friction was found to be between 25° and 29° for the box core samples from BS-BC-252. The angle of internal friction was found to be as low as 19° for a gravity core sample from BS-GC-312 at 128 cm depth. The lower strength of the gravity core sediment is probably the result of sediment structure disturbance caused by de-gassing of the core. Visual observations at the time of subsampling indicated significant general disturbance to these deeper sediments whereas the box core de-gassing seemed to be concentrated in localized "tubes". In any event, the Baltic Sea sediments exhibit very low shear strength behavior but the results are in a range typical for sediments with very high porosity. Test results are still being analyzed to determine other stress-strain parameters of interest to the program. Testing is continuing on undisturbed and remolded samples from various locations and depths at the study site to determine vertical and lateral variability of strength parameters. We also intend to study the relationship between geotechnical and geoacoustic parameters with a new triaxial acoustic measurement system that is nearing completion.

Selected samples were obtained from a gravity core and a box core from the Baltic Sea site to determine their mineralogical composition. X-ray diffraction tests were completed on five samples (three from box core 238-BS-BC and two from gravity core 029-BS-GC) at different depth intervals to identify the mineral fractions of the Baltic Sea sediments. The first set of tests were performed on the bulk samples using the powder diffraction technique. Diffraction patterns showed strong peaks of quartz and smaller peaks of illite, chlorite and plagioclase. Two of the samples also indicated the presence of smectite. In order to better identify the clay minerals, a second set of tests were performed on the fraction of the sediments smaller than 2 μm size. Oriented aggregates on silver filters were used for better identification of the clay minerals. The samples were spiked with 10% talc to enable preliminary quantitative comparisons of mineral contents between samples. These diffraction patterns clearly indicated the presence of smectite and also showed evidence of kaolinite. X-ray diffraction tests were also conducted on glycolated

samples of the < 2μm fraction to confirm the presence of smectite. The results indicate that smectite is indeed present but probably not in an amount significant enough to dominate the sediment characteristics. Efforts are being made to correlate experimentally determined material properties, such as Atterberg Limits, with variations in mineralogy and organic content. Additional quantitative mineralogical analysis is recommended.

Organic content determinations were performed in accordance with ASTM D2974-87 on fifteen samples from across the Baltic Sea site. The organic content ranges between 9 and 17%, with an average of 12%. It is likely that the organics play an important, and perhaps dominant role, in controlling many of the engineering properties and behavior of these sediments.

Geoacoustic Microstructural Modeling

Geoacoustic modeling continued with the numerical simulations of saturated particulate sediments using the discrete element method. Pore fluid effects were included in our elastohydrodynamic contact law which was used in the numerical scheme. Details of the numerical methodologies and the development of this contact model were given in the FY 1993 annual report. During this past year, activities included additional one-dimensional verification studies, two-dimensional random particulate modeling, and the initiation of a laboratory experimental program to study compressional wave propagation in reconstituted sediments.

Several computer simulations of two-dimensional granular sediment models have been conducted. An example of one such assembly, shown in Figure 2, was created using one of our computational random media generators. These generating codes can create large random particulate assemblies with varying degrees of microstructural fabric such as porosity, coordination number, particle contact normal and branch vector distributions, void vectors, etc. Figure 2 also illustrates the polar distribution of the branch vectors (vectors between adjacent particle mass centers) for the assembly. Our studies have been focusing on establishing relationships between the sediment microstructure and the wave propagational characteristics determined by discrete element simulation. The particles in this simulation were 2mm in diameter and had the material properties of quartz. The given assembly was subjected to horizontal and vertical wave propagation. Horizontal propagation was created through simultaneous loading of particles along the left side of the assembly with a triangular time dependent pulse of duration 5 μs with a peak value of 2 N to simulate a wave front acoustic pressure pulse of 10^6 N/m^2. The transmitted wave output (measured by the inter-particle contact forces) was collected among the particles along the right side of the assembly. Vertical wave propagation was modeled in a similar fashion. An example of this transmission computer simulation is shown in Figure 3 which illustrates the normalized average wave transfer through the assembly for horizontal and vertical propagation for a water saturated system with an inter-particle gap spacing of 0.1 μm. It can be observed that much larger wave transmission occurs in the horizontal direction in comparison to the vertical which correlates with the branch vector fabric. Figure 4 illustrates the effect of the inter-particle gap spacing on the horizontal wave transmission for the two-dimensional assembly. Clearly the model sediment with a larger gap spacing shows a larger attenuation and a longer arrival time. A considerable number of such assemblies are now being investigated and a comprehensive correlation of wave propagation with sediment fabric is being completed.

In order to validate our geoacoustic modeling, an experimental program has been initiated. A special sediment sample holder has been designed and constructed to be used in conjunction with our acoustic data logger (MSCL), and a schematic of this device is shown in Figure 5. The sample holder was designed to allow direct contact (through a membrane) between the sediment sample and the excitation and receiving transducers, thus allowing more accurate measurements of the wave speed and amplitude attenuation to be made. The device has been built and preliminary tests have just been begun.

Panama City, FL Core Processing

Eight high-quality gravity cores were collected during the August 1993 Panama City, FL cruise, ranging in length from 20 to 51 cm (P.C-GC-575, -577, -587, -596, -597, -622, 623 and -628). All cores have been processed using the MSCL to determine compressional wave velocity, bulk density and attenuation at closely spaced intervals (1 cm). Each core was scanned in two mutually perpendicular directions. The results are presented in the more detailed annual report.
One of the cores, PC-GC-577, has been subsampled for laboratory testing. Three undisturbed 5.08 cm diameter triaxial and two 5.08 cm consolidation/permeability samples were collected, as well as numerous water content and bulk samples. Grain size test results shown in Table 3 indicate the sediment from this core to be a poorly graded sand, consisting primarily of medium sized sand with lesser amounts of fine sand, coarse sand, and gravel-size shell fragments. The percentage of medium sand decreases somewhat below the top 16 cm (19-87% versus 67-73% below 16 cm), whereas the percentages of fine sand, fines, and gravel-size shell fragments increase below 16 cm. Triaxial and consolidation/permeability testing of the undisturbed and remolded samples will begin shortly.

Publications

A. Ocean Sciences Meeting, February, 1994, San Diego, CA (Abstracts and Presentations).

1. "Variability of Geotechnical Properties of High Porosity Surficial Sediments at the CBBL/SRP Baltic Sea Site." A.J. Silva, H.G. Brandes and G.E. Veyera.
2. "Compressibility and Permeability Behavior of High Porosity Surficial Sediments at the CBBL/SRP Baltic Sea Site." G.E. Veyera, A. Ag., A.J. Silva and H.G. Brandes.
3. Rheological Characteristics of High Porosity Surficial Sediments at the CBBL/SRP Baltic Sea Site." H.G. Brandes, G.E. Veyera and A.J. Silva.
4. "Discrete Element Microstructural Modeling of Geoacoustic Wave Propagation in Saturated Granular Seabed Sediments." M.H. Sadd and Q.-M. Tai.

B. Special Issue of *Geo-Marine Letters* (Fall, 1994).

1. "Geotechnical Characterization of Sediments in Eckernförde Bay, Baltic Sea." A.J. Silva, W.H. Bryant, H.G. Brandes, N. Slowey and G.E. Veyera.
2. "Stress State and Permeability Characteristics of High Porosity Sediments in Eckernförde Bay, Baltic Sea." H.G. Brandes, A.J. Silva, A. Ag, and G.E. Veyera.
3. "Variability of Sediment Properties in Upper Benthic Boundary Layer in Eckernförde Bay, Baltic Sea." W.H. Bryant, A.J. Silva, N. Slowey and H.G. Brandes.

C. Acoustical Society of America Meeting, November, 1994, Austin, TX (Abstracts and Presentations).

1. "A Propagation Model for Wave Motion in Saturated Granular Sediments." M.H. Sadd, A. Gautam, A.J. Silva and G.E. Veyera.
2. "Acoustical Properties of Undisturbed Sands from the West Florida Sand Sheet." H.G. Brandes, A.J. Silva.

D. Theses in Preparation; to be completed by Spring, 1995.

1. Ajoykumar Ag: "Consolidation and Permeability Behavior of High Porosity Baltic Sea Sediments." Department of Ocean Engineering.
2. Adhikari Gautam: "Wave Propagation in Saturated Granular Materials." Department of Mechanical Engineering.

Note: These theses are being written in manuscript format and will be submitted to an appropriate journal for publication (probably ASCE or ASTM).

Summary

The second year (FY94) of the CBBL/SRP program at the University of Rhode Island/Marine Geomechanics Laboratory (URI/MGL) has been very active and productive. Several important improvements have been made to the MGL facilities and we are awaiting delivery of the acoustic system being installed in one of our triaxial compression cells by NRL. During the 1994 Eckernförde research cruise, we obtained additional samples for the laboratory testing program and made comparative geotechnical measurements on pressurized and depressurized gravity cores.

Extensive laboratory testing including physical properties measurements, triaxial stress-strain-time behavior and consolidation/permeability behavior, has been conducted on Baltic Sea sediments. The sediments can be generally characterized as having very high void ratios ($e = 5.5$ to 7.4), being very compressible ($C_c = 2.0$ to 5.8), having low to moderate permeabilities (typically 10^{-5} to 10^{-7} cm/s), and exhibiting decreasing overconsolidation with depth. In addition, some physical properties and acoustic measurements have been made on sediments from the Panama City, FL site and other cores are currently being analyzed. Based on our experience with the Baltic and Panama City sediments, we have developed specialized preparation/testing procedures and improved our testing facilities. With these improvements and our acoustic triaxial system, we will be intensifying our studies to evaluate the relationships between geoacoustic characteristics and geotechnical properties/behavior of seabed sediments for the CBBL/SRP program.

Mineralogical analyses (X-ray diffraction) of five Baltic Sea samples show strong peaks of quartz with smaller peaks of illite, chlorite, and plagioclase; and a definite presence of smectite. Quantification of the dominant minerals has not been completed. Organic contents of the surficial Baltic Sea sediments range from 9 to 17% with an average of 12%. It is likely that organics play a very significant role in controlling the engineering properties and behavior of these sediments.

Geoacoustic modeling continued with numerical simulations of saturated particulate sediments using the discrete element techniques that incorporate our new elastohydrodynamic interparticle contact law. Several two-dimensional granular sediment models have been developed, and wave propagation simulations have been conducted using these models. Results indicated that wave propagation was dependent on the interparticle gap spacing, the branch vector distributions of the models and other pertinent fabric variables. Preliminary experimental work has been initiated to test actual sediment materials using our acoustic data logger (MSCL) and a special sample holder.

Processing and testing of the Panama City cores is proceeding. Some of the grain size analyses are presented in this report.

Several publications, reports, and presentations have been completed and others are in various stages of preparation. A list of eleven (11) titles are contained in this report.

Table 1. Additional CRD Consolidation/Permeability Tests: Baltic Sea Sediments*.

Sample	Depth (cm)	Water Content (%)	Compr. Index (C_c)	Precon. Stress (kPa)	Overbur. Stress [a] (kPa)	OCR	k^b (cm/s)
BC-40	32	236	3.4	2.9	0.5	3.4	4×10^{-5}
BC-225	36	244	3.2	2.3	0.6	3.7	9.8×10^{-7}
BC-225(R)	37	218	2.0	---	---	---	1.6×10^{-6}
BC-252 (R)	29	282	3.0	---	---	--	3.7×10^{-6}
BC-264 (H)	33	275	3.5	2.3	0.6	4.1	2.0×10^{-6}
BC-264 (V)	36	244	3.5	2.5	0.6	4.4	3.4×10^{-6}
GC-304	41	280	3.5	4.6	2.4	1.9	7.2×10^{-5}
GC-304	150	259	2.9	3.6	2.6	1.4	2.8×10^{-6}
GC-318	144	221	2.7	3.3	2.5	1.3	3.2×10^{-4}
GC-318	157	245	4.1	3.7	2.7	1.4	7.5×10^{-5}

* Also see First Ann.Rep., FY 93, by Silva et al.

[a] Calc. assuming an ave. density of $1.2 gm/cm^3$

[b] Coef. of Permeability at in-situ void ratio

OCR = Overconsolidation Ratio

R=Remolded, H=Horizontal, V=Vertical.

Table 2. CIU Triaxial Tests, Baltic Sea Sediments.

Sample	Depth (cm)	Water Content (%)	Consol. Stress (kPa)	σ_1-σ_3 max. (kPa)	σ_1/σ_3 max. (kPa)	Failure Strain (%)	A_f
GC-312	128	242	5.2	4.6	1.01	2.7	0.10
BC-252 (1)	35	178	2.3	2.15	1.01	3.2	0.37
BC-252 (3)	35	205	3.8	4.0	1.01	3.4	0.43

Table 3. Grain Size Distribution Panama City, FL Core No. PC-GC-577.

Depth (cm)	Gravel Size[a] (%)	Coarse Sand[b] (%)	Medium Sand[c] (%)	Fine Sand[d] (%)	Fines[e] (%)	Mean Grain Size $\overline{\Phi}$
0-5	0	6	82	12	0	0.30
5-10	1	5	79	15	0	0.60
10-16	1	7	87	15	0	0.39
16-21	4	7	70	18	1	0.40
21-26	5	8	70	16	1	0.26
26-31	9	9	67	14	1	0.09
31-37	1	8	73	17	1	0.44
37-42	2	7	73	16	2	0.42
42-46	2	9	72	15	2	0.43

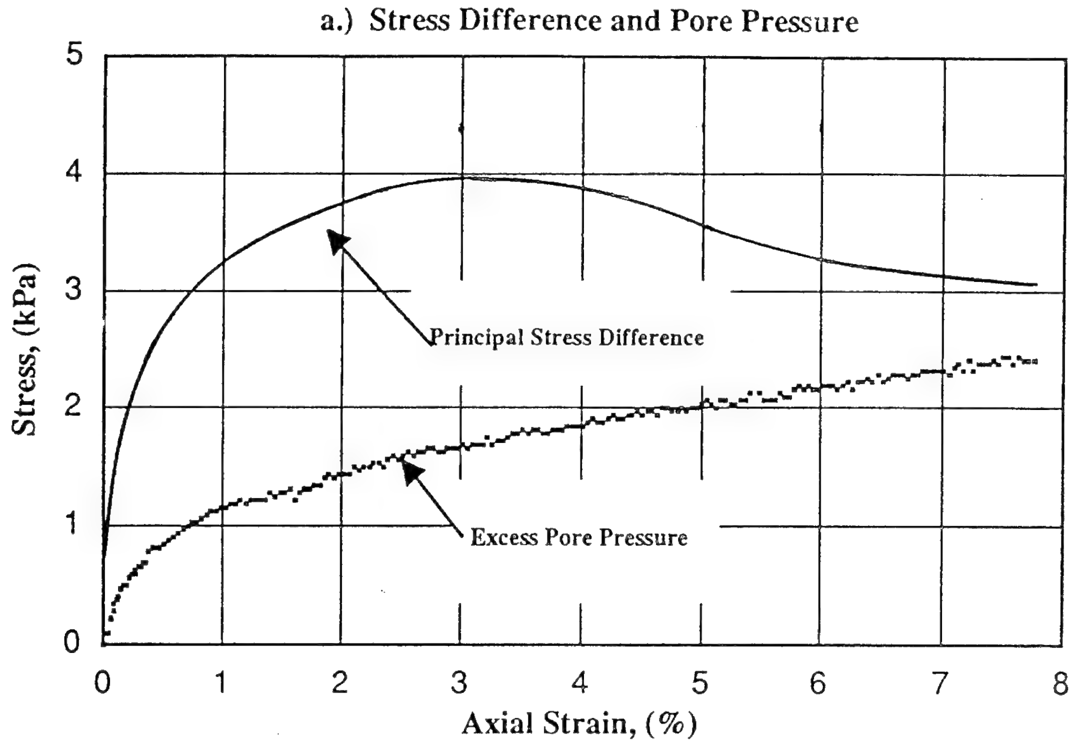
[a] 4.75mm < gravel size (shell fragments)

[b] 2mm < coarse sand < 4.75mm

[c] .425mm < medium sand < 2mm

[d] .062mm < fine sand < .425mm

[e] .062mm > fines (silt and clay)



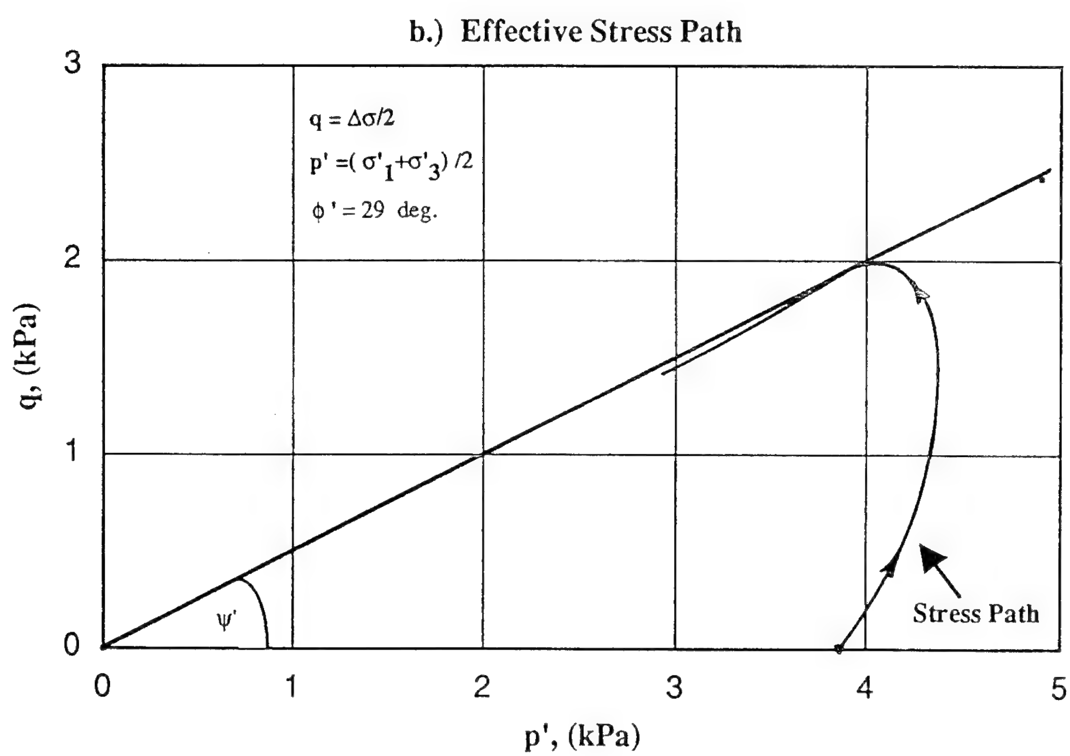


Figure 1 CIU Strength Test
BS-BC-252 27-42cm

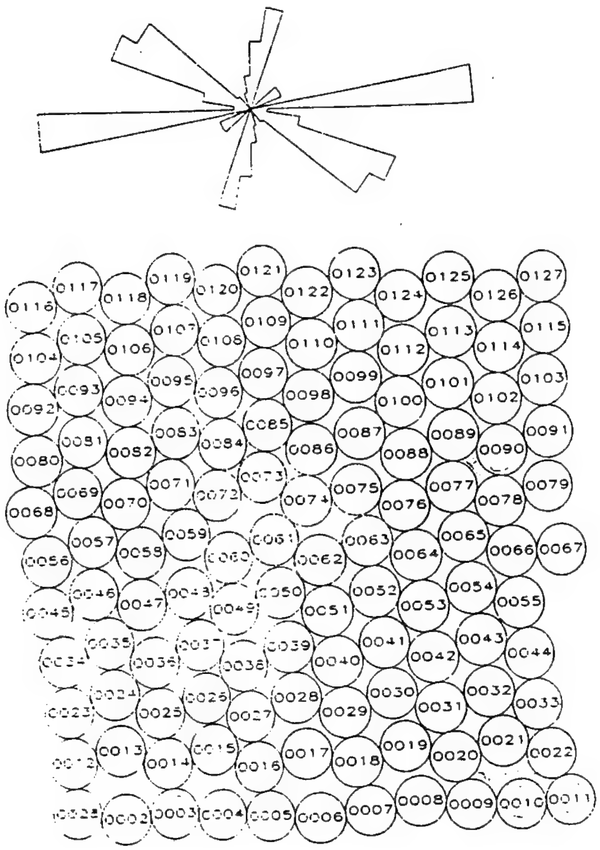


Figure 2. Two-Dimensional Granular Model.

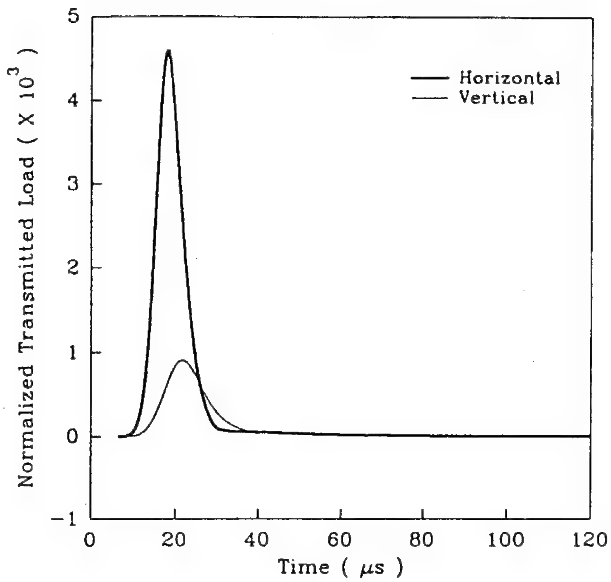


Figure 3. Average Wave Transmission.

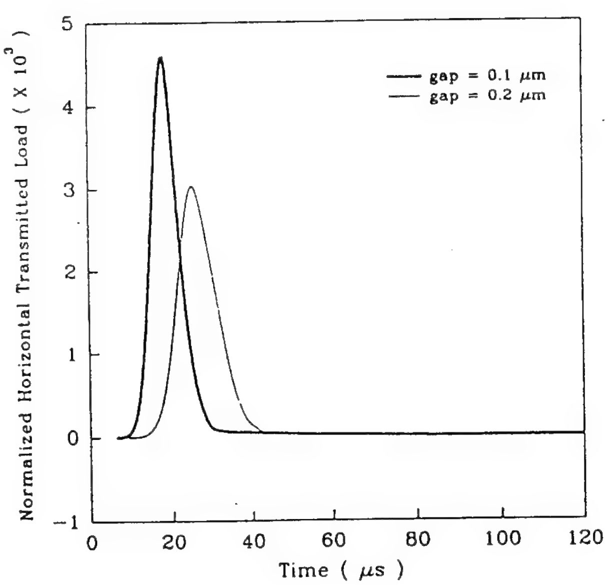


Figure 4. Inter-Particle Spacing Effects on Wave Transmission.

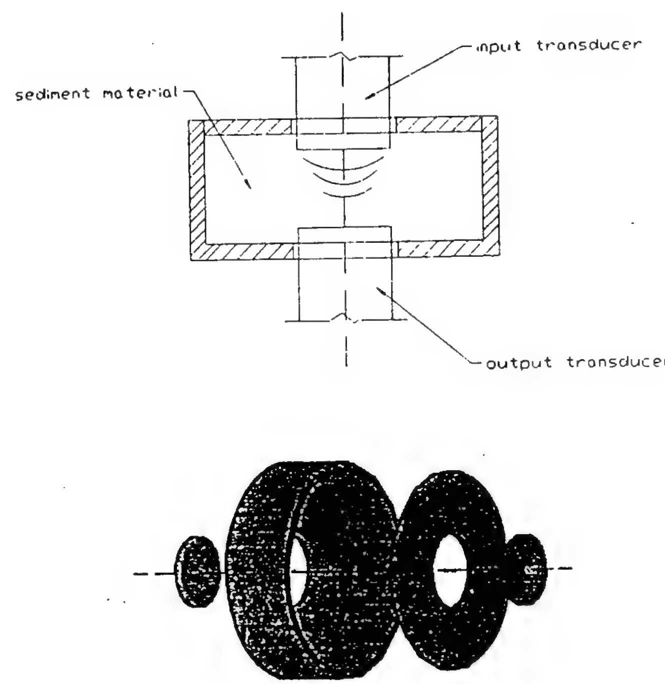


Figure 5. Acoustic Sediment Sample Holder

2.16 High-Frequency Acoustic Boundary Scattering Measurements in Eckernförde Bucht, Germany and Off Panama City, Florida (Principal Investigator: S. Stanic)

1994 CBBL PROGRESS REPORT

S. STANIC ET AL.

During the June/July 1994 CBBL experiments a series of high-frequency bottom penetration measurements were taken. A multi element hydrophone array was buried in the muddy sediments of Eckernforde Bucht, Germany. These hydrophones provided measurements of the normal incidence acoustic insertion loss across the water sediment interface, correlation function estimates, and estimates of the transmission loss through the gassy sediments as a function of depth and frequency.

The measurements were taken using sources hanging over the side of the planet. The frequencies ranged from 15 kHz to 40kHz. the data was recorded using a small digital data acquisition system provided by Kinetics Systems. The data was complex basebanded to 5kHz and the seven buried hydrophone channels were sampled at 20kHz. The depth of the hydrophones are shown in table

TABLE I

CHANNEL NO.	HYDROPHONE DEPTH (CM)
1	SURFACE
2	3 CM
3	10 CM
4	20 CM
5	40 CM
6	50 CM
7	70 CM

Reverberation levels for the coarse sediment in Panama City have been calculated. Figure 1 shows these results and their comparison to predictions made using Jackson's model. The free parameter is the value of the volume loss parameter.

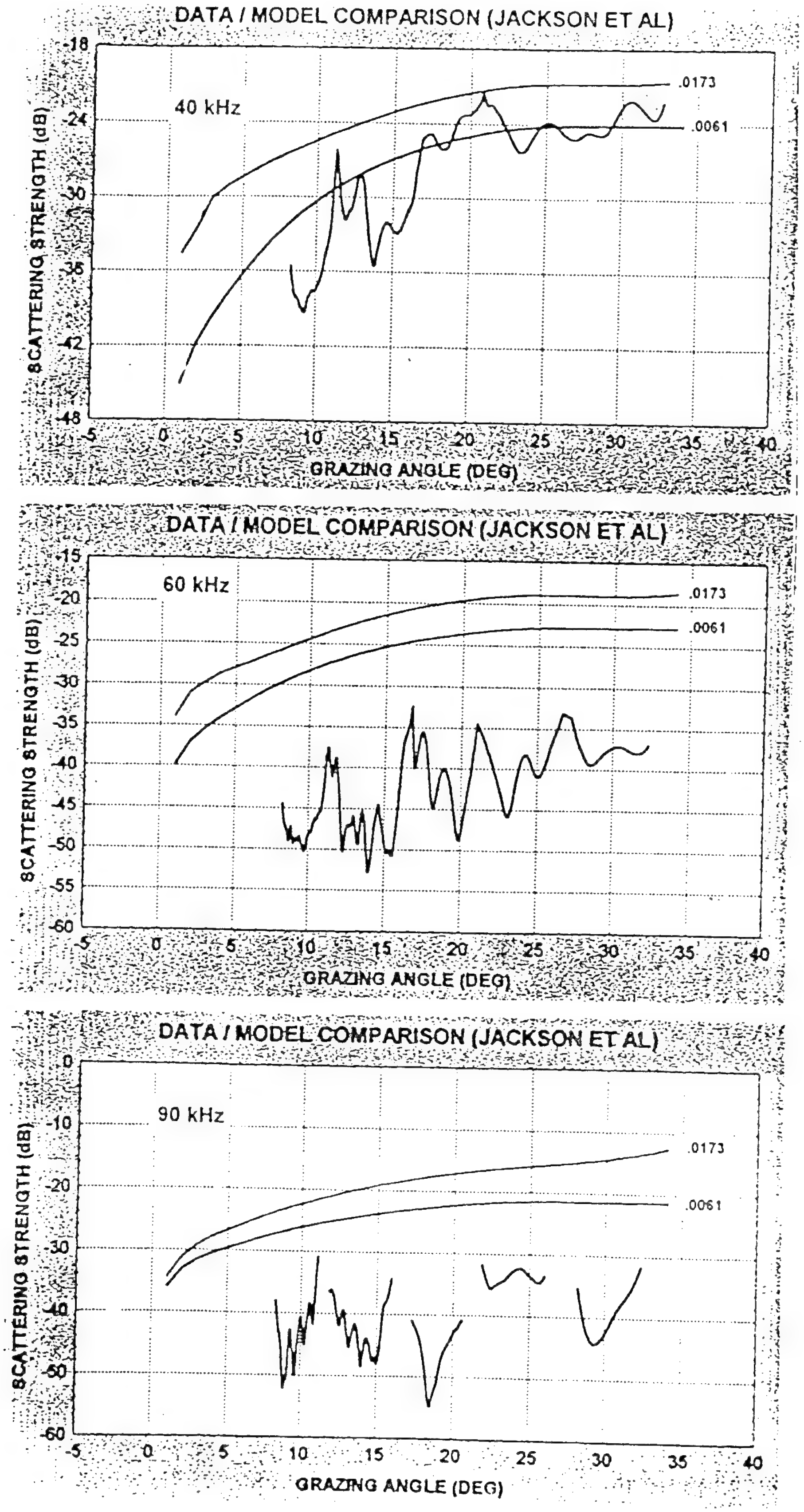

DATA / MODEL COMPARISON (JACKSON ET AL)
40 kHz
.0173
.0061
SCATTERING STRENGTH (dB)
-18
-24
-30
-36
-42
-48
-5
0
5
10
15
20
25
30
35
40
GRAZING ANGLE (DEG)
DATA / MODEL COMPARISON (JACKSON ET AL)
60 kHz
.0173
.0061
SCATTERING STRENGTH (dB)
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
-5
0
5
10
15
20
25
30
35
40
GRAZING ANGLE (DEG)
DATA / MODEL COMPARISON (JACKSON ET AL)
90 kHz
.0173
.0061
SCATTERING STRENGTH (dB)
0
-10
-20
-30
-40
-50
-60
-5
0
5
10
15
20
25
30
35
40
GRAZING ANGLE (DEG)

FIGURE 1

2.17 Experimental and Theoretical Studies of Near-Bottom Sediments to Determine Geoacoustic and Geotechnical Properties (Principal Investigator: R.D. Stoll)

CBBLSRP FY94 YEAR-END REPORT

Robert D. Stoll
Lamont-Doherty Earth Observatory of Columbia University
Rte. 9W, Palisades, New York 10964

EXPERIMENTAL AND THEORETICAL STUDIES OF NEAR-BOTTOM SEDIMENTS TO DETERMINE GEOACOUSTIC AND GEOTECHNICAL PROPERTIES

INTRODUCTION

This report summarizes the participation of the Lamont-Doherty Earth Observatory (LDEO) team in the Coastal Benthic Boundary Layer, Special Research Program (CBBSRP) during the time period October 1, 1993 to October 24, 1994. The LDEO team consists of the following personnel:

Prof. Robert D. Stoll - LDEO
Dr. Edgar O. Bautista - LDEO
Mr. Ivars Bitte - LDEO
Prof. Roger Flood - SUNY, Stony Brook

Our main objectives during the second year of the program were to analyze data obtained during the cruises in FY 93 at FWG, LaSpezia, Italy and Panama City Florida, to improve and extend the capabilities of the equipment designed and built during the first year and to begin theoretical studies of the relationship between sediment properties such as shear strength and shear modulus or shear-wave velocity. The shear strength, which is a large strain parameter usually expressed as undrained shear stength, s_u, in fine-grained sediments or angle of internal friction in granular sediments, plays a fundamental role in determining the penetration and stability of mines deployed on the seafloor. On the other hand the shear-wave velocity is a small strain parameter which has been studied extensively in recent years because of its importance in the determination of bottom loss in long range wave propagation in shallow water.

During the first year of the CBBLSRP a number of new tools were developed to measure the properties mentioned above. These include a torsional wave source which generates Love waves in the sediment and a quasistatic cone penetrometer designed to measure shear strength. In addition, a p-sv wave source which uses a 22-caliber blank cartridge was developed to generate low amplitude pulses with somewhat higher frequency content than the conventional airgun. These new tools are described in detail in a paper which will appear in the Jour. Acoust. Soc. Am. in November (Stoll et al, 1994b). During FY 94 a new version of the cone penetrometer was developed to permit deeper penetration into the sediment (up to 2m) and tc allow high-frequncy attenuation experiments to be performed in the near-botoom sediments. This new equipment is described in this report.

Another new piece of equipment, which was directly inspired by our field work in the CBBL

program is an expendable free-fall penetrometer developed in a joint program with SACLANT Undersea Research Center under ONR sponsorship (E. Estolate, U. S. Liaison with SACLANCEN). In this work a standard bathythermograph (XBT) was modified to measure deceleration and resonant frequncy as the probe impacts the seafloor. Analysis of the contact signature allows estimates of both insitu shear strength and shear modulus which are important in mine counter measures work as mentioned above.

As stated in our original proposal to the CBBLSRP, one of our primary goals is to obtain enough data from insitu experiments to establish a convincing correlation between shear strength and shear wave velocity. At the present time most of our data supports the existance of such a relationship and an example of the results of a number of field tests is shown in Fig. 7.

NEW EQUIPMENT

2-meter Penetrometer

A photograph of the new 2-meter penetrometer is shown in Fig. 1. The base of the unit is composed of a 5 ft. square truss made of aluminum channel and a central plate which supports the drive motor and the bottom of the vertical leads which guide the motion of the penetrometer rod. Lead weights, each weighing 125 lbs., are bolted to the aluminum channel in a symmetric pattern around the base. The weights are easily removed from the base in order to facilitate transportation and handling.

The power unit of the penetrometer is a fractional horsepower DC motor which can either be driven by storage batteries which would replace some of the lead weights on the base or by current sent down a cable from the surface in situations where the depth is not so great that the cable resistance becomes prohibitive. We are currently operating the unit in the latter mode using a 500 watt variable voltage supply attached to the ships power. Since only 30 to 40 volts are required, the system is simple and safe and it lends itself to use on small boats which can supply only a limited amount of power.

The principal requirement of the vessel used to deploy the penetrometer is that it have a U or A frame or a crane that is able to lift and handle approximately 2000 lbs. and can accomodate the 9 ft. height of the penetrometer tetrapod assembly. We have successfully deployed the penetrometer several times from a 40 ft. research vessel in New York Harbor (with calm seas) however a somewhat larger vessel would be desirable when working in less sheltered water.

The cone penetrometer attached to the lower end of the drive rod is the ASTM standard size and shape (60° cone with 10 cm^2 area) instrumented with a silicon strain-gage bridge and is much more sensitive than conventional cones that are designed for deeper penetration and higher loads. For this reason it is possible to measure small changes in the penetration resistance of the sediment column and to obtain meaningful results in soft sediments. The bridge output is transmitted to the surface using a current loop driver which allows the signal to be transmitted over a long cable without degradation. At the recording ship the signal is routed to an analog-to-digital converter and stored in an ASCII file on a portable microcomputer. Load at the tip is recorded every .25 in. of penetration

and a continuous record of penetration resistance vs depth is displayed on the computer screen. The nominal output sensitivity of the measuring system is currently set at 4 mv/lb although this is easily changed to a higher value if desired. The system is calibrated on deck at the beginning of each deployment.

An example of the penetration resistance measured in a shelly sand and a soft shelly silt are shown in Figs. 2 and 3. In Fig. 2 the test was terminated when the load reached 900 lb so that only about 1.2 m of penetration was achieved because the total weight of the penetrometer was reduced to 1000 lbs in order to avoid overloading the small winch that was available.

In order to verify the usefulness of the penetrometer for measuring the thickness of a sand layer over soft sediment, several laboratory experiments were performed on a layered soil system in the laboratory. In these tests a layer of soft Bentonite clay was placed in the bottom of a 55 gal drum and covered with a layer of saturated sand. Pictures of the test setup are shown in Fig. 4. The resistance of both loose and dense sand layers was investigated with the results shown in Figs. 5 and 6. In both cases the penetration resistance in the upper part of the sand layers depends on the internal friction and it therefore increases with depth reflecting the influence of increasing overburden pressure on the tip resistance. However, when the tip reaches a depth that is about six cone diameters above the top of the clay layer, the resistance rapidly decreases as the cone begins to "feel" the proximity of the soft layer. Finally, as the cone enters the soft layer, the penetration resistance becomes constant as the cone penetrates further, with the cone resistance dependent on the undrained shear strength of the clay. Thus it is possible to determine the position of the interface between sand and clay to an accuracy of one or two centimeters with proper interpretation of the penetration curve.

DATA INTERPRETATION

We have developed a number of programs for inverting the data obtained in field experiments particularly those involving interface waves. In most cases we have derived models of the sediment column (velocity vs depth) by analyzing the dispersion of either Scholte or Love waves generated by an impulsive source. This work is described in a series of papers in the Journal of the Acoustical Society of America (Stoll et al, 1991, Stoll et al, 1994a, Stoll et al, 1994b, Bautista and Stoll, 1994) The last two papers in this series were completed during the current FY and they represent a significant portion of the theoretical work carried out under the grant during FY 94.

Shear wave velocities from the models derived as described above are currently being compared with cone penetrometer measurements at each of the different experimental sites. A preliminary example of the results of this sort of correlation is shown in Fig. 7 wherein average measured values of cone penetration resistance and shear wave velocity at different depths are plotted. Most of the data are from the Panama City experiments. The bands labeled loose and dense were derived from the penetration curves shown in Figs. 5 and 6 by using the measured penetration resistance, which is linearly proportional to overburden pressure, and calculated values of shear wave velocity based on the empirical formula given by Bryan and Stoll which predicts a parabolic variation of velocity with increasing overburden. (e.g., see Eq. 6.2 in Stoll (1990)). Thus when overburden pressure is parametrically eliminated, the result is a parabolic variation which is an excellent match for our field data.

REFERENCES

Bautista, E. O. and R. D. Stoll (1994) "Measuring seafloor geoacoustic properties using Love waves," submitted to J. Acoust. Soc. Am.

Stoll, R. D. (1990) Sediment Acoustics, (Springer-Verlag, Berlin) p. 116.

Stoll, R. D., Bryan, G. M., Mithal, and R. Flood (1991) "Field experiments to study seafloor seismo-acoustic response," J. Acoust. Soc. Am. **89**, 2232-2240.

Stoll, R. D., Bryan, G. M. and E. Bautista (1994a) "Measuring lateral variability of sediment geoacoustic properties,"J. Acoust. Soc. Am., **96,** 427-438.

Stoll, R. D., Bautista, E. and R. Flood (1994b) "New tools for studying seafloor geotechnical and geoacoustic properties," J. Acoust. Soc. Am., **97**.

FIGURE CAPTIONS

Fig. 1. Photographs of penetrometer (version 1) showing overall layout and closeup of drive and tip mechanism. Weights around base weigh 125 lbs each.

Fig. 2. Penetration resistance (kg/cm^2) in shelly sand, New York harbor.

Fig. 3. Penetration resistance (kg/cm^2) in an area of soft shelly silt, New York harbor.

Fig. 4. Photographs showing laboratory setup used to measure penetration resistance in a layered system consisting of sand over soft Bentonite clay.

Fig. 5. Penetration resistance in a layered system consisting of loose sand over soft Bentonite clay.

Fig. 6. Penetration resitance in a layered system consisting of dense sand over soft Bentonite clay.

Fig. 7. Cone penetration resistance versus shear-wave velocity. All data from Gulf of Mexico near Panama City, Florida except asterisk which is from New York Harbor.

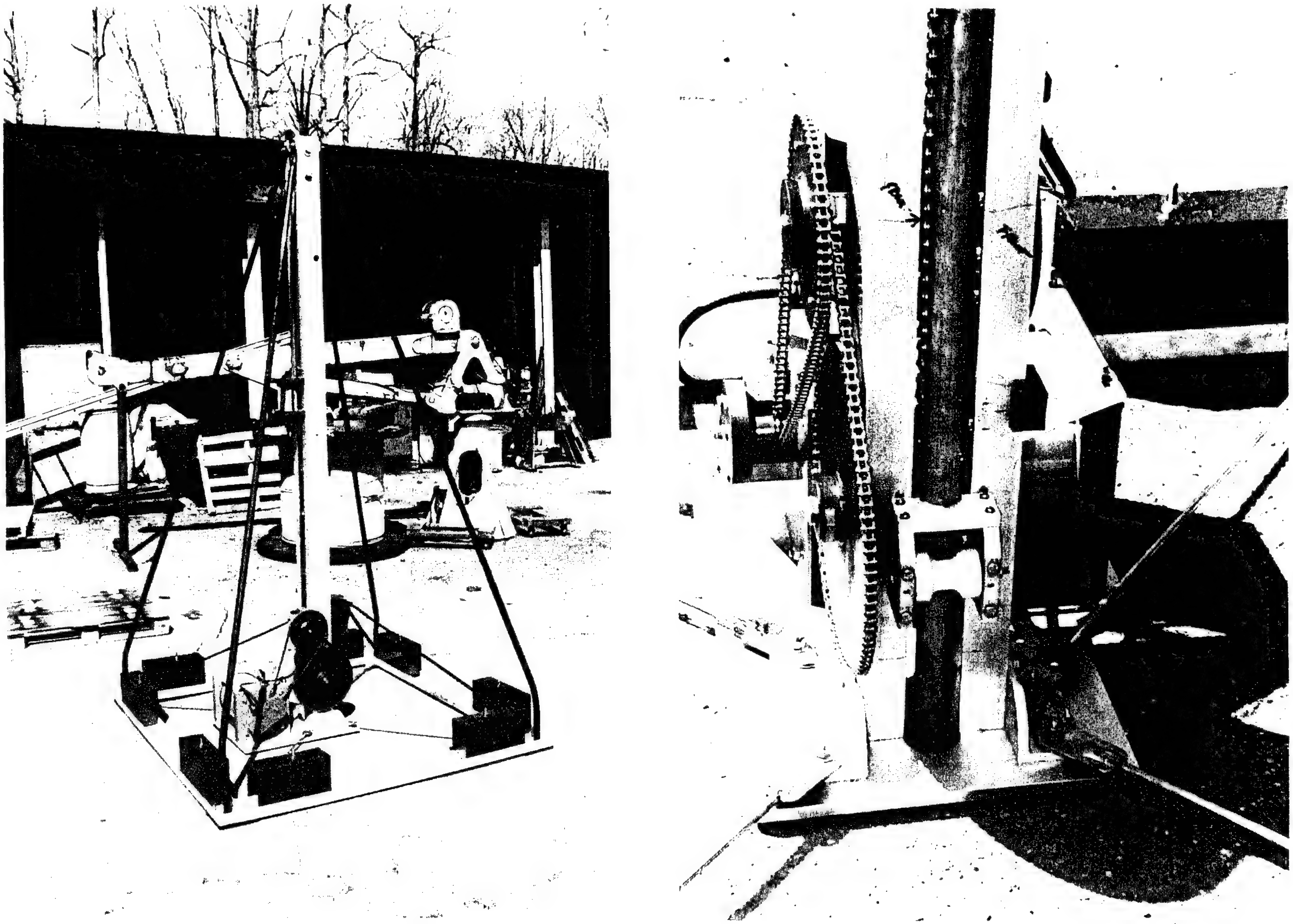


Fig. 1. Photographs of penetrometer (version 1) showing overall layout and closeup of drive and tip mechanism. Weights around base weigh 125 lbs each.

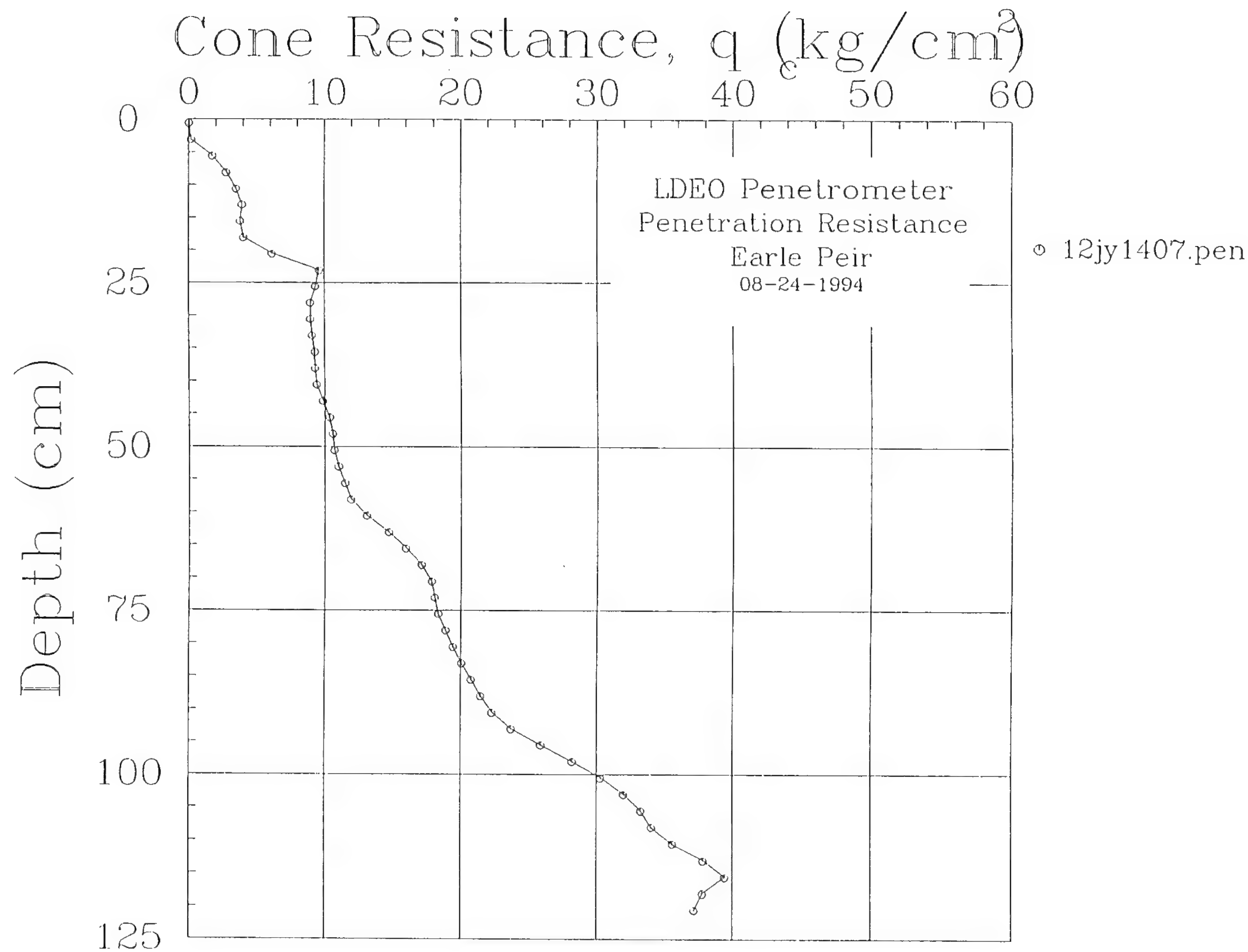


Fig. 2. Penetration resistance (kg/cm$_2$) in shelly sand, New York harbor.

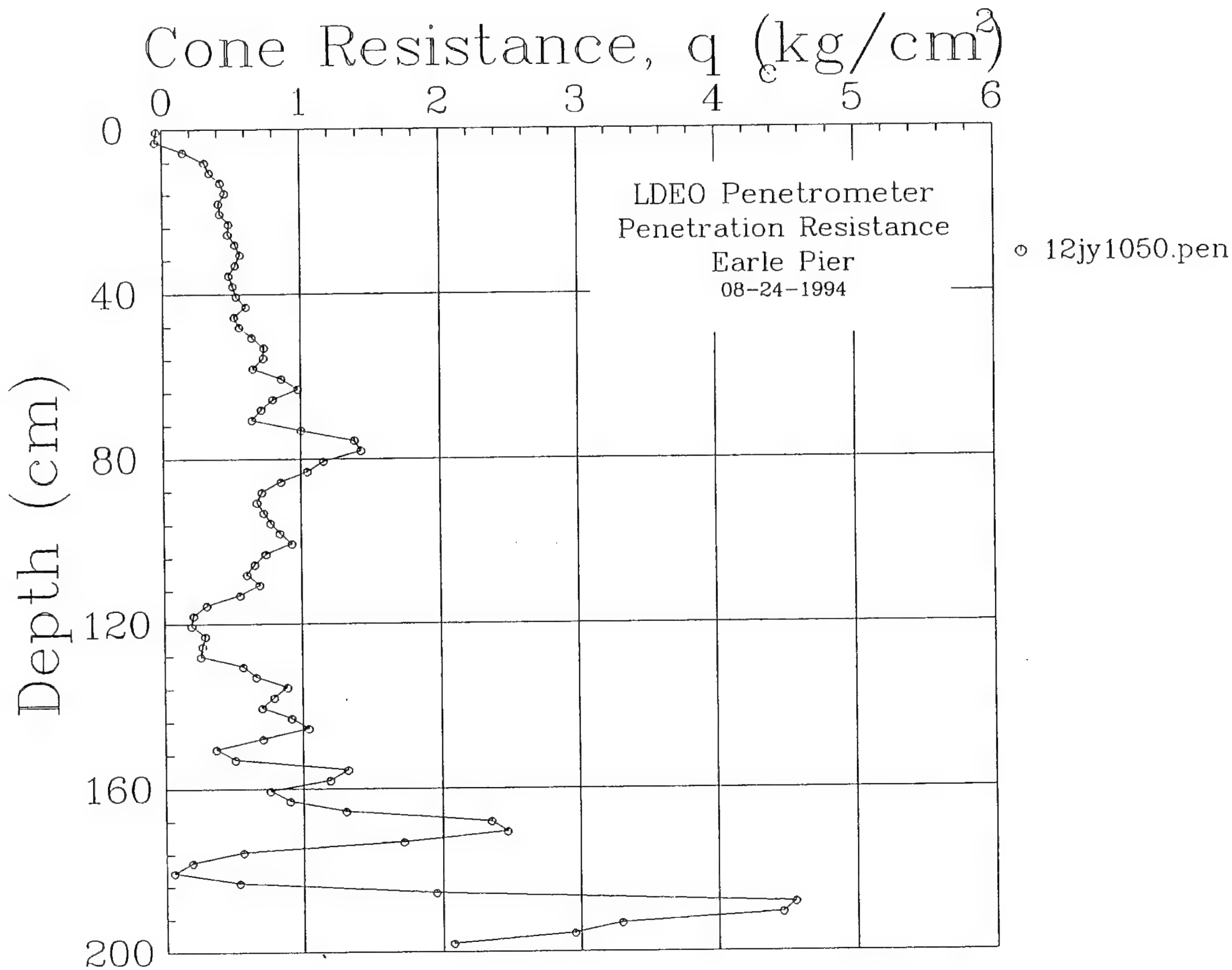


Fig. 3. Penetration resistance (kg/cm^2) in an area of soft shelly silt, New York harbor.

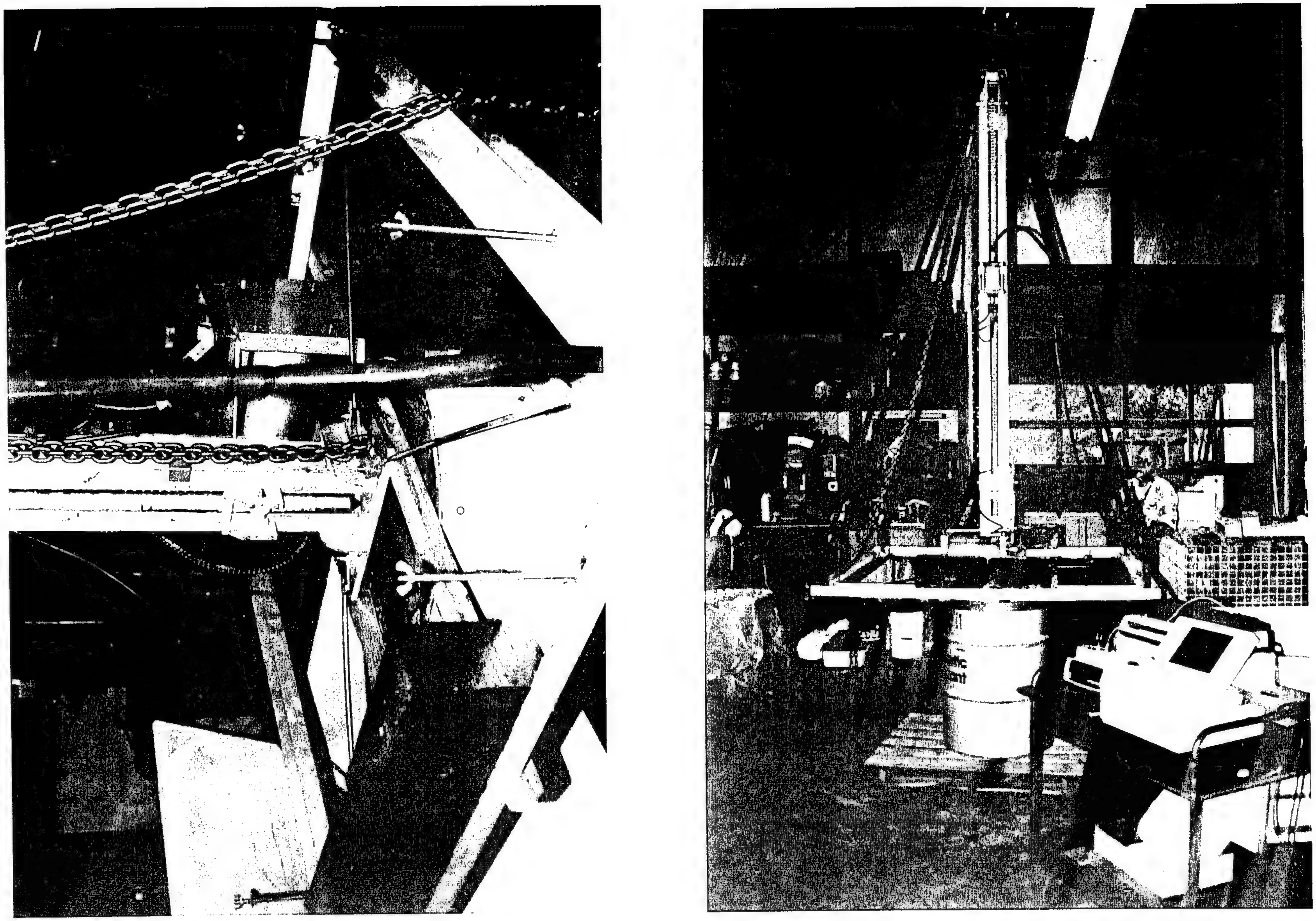


Fig. 4. Photographs showing laboratory setup used to measure penetration resistance in a layered system consisting of sand over soft Bentonite clay.

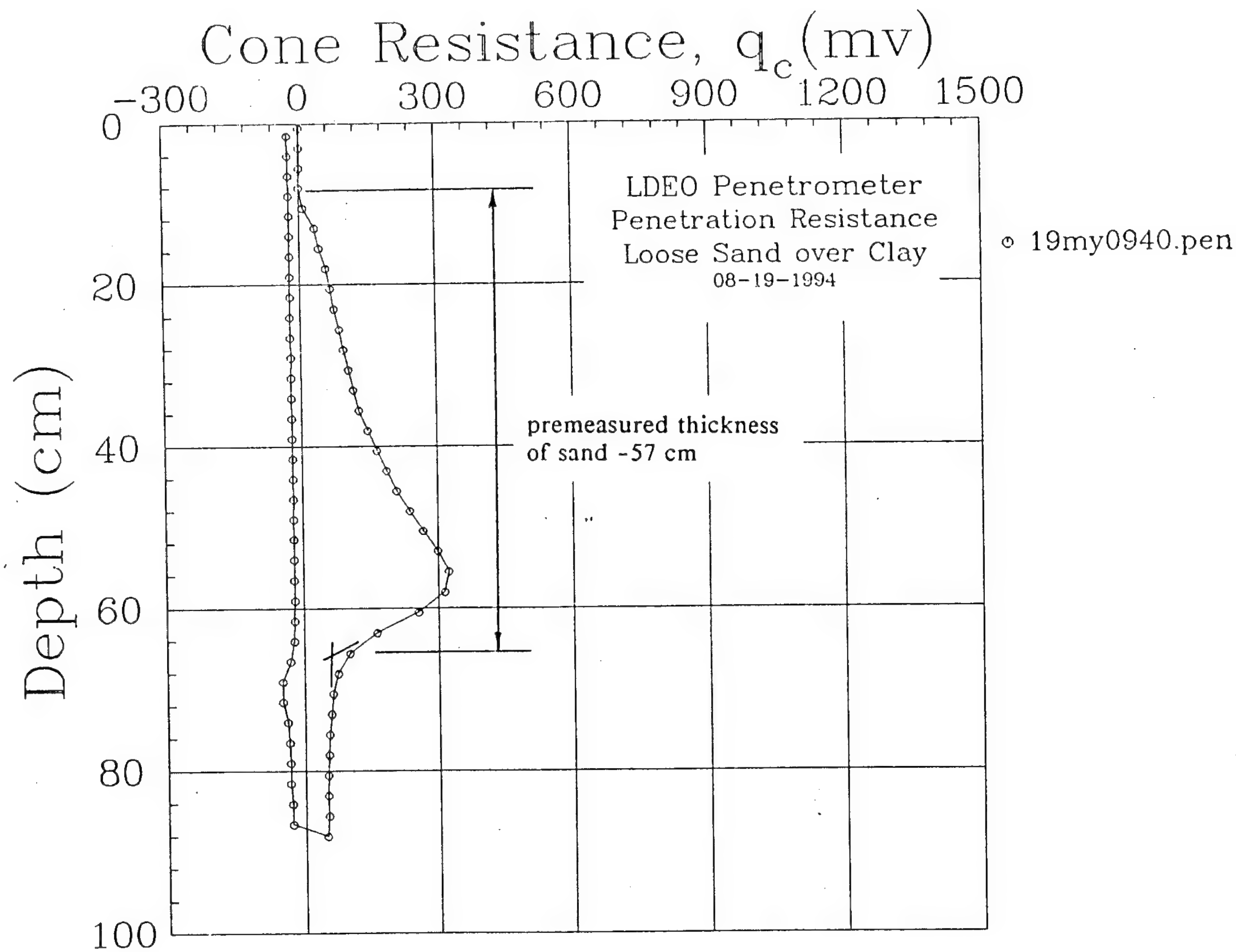


Fig. 5. Penetration resistance in a layered system consisting of loose sand over soft Bentonite clay.

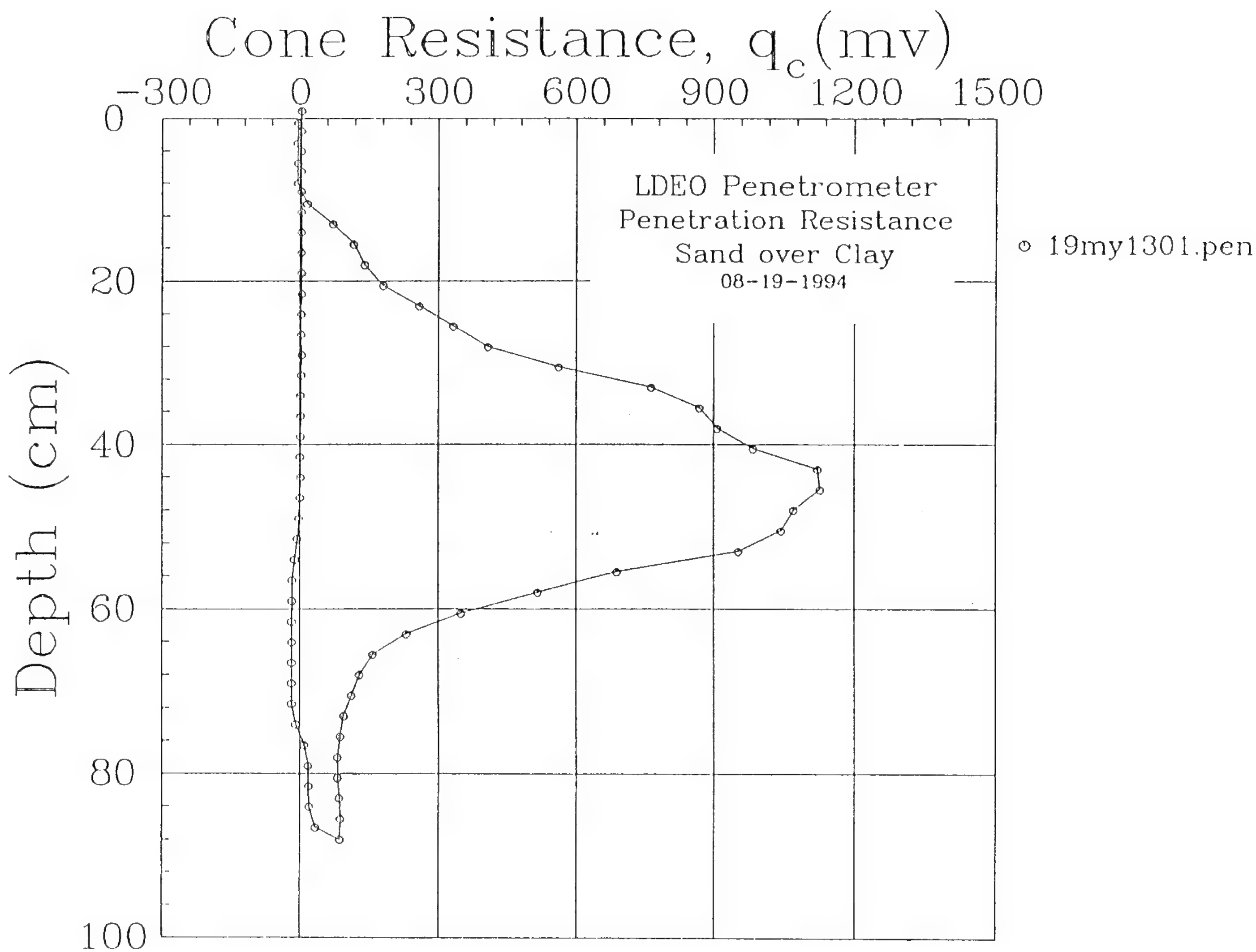


Fig. 6. Penetration resistance in a layered system consisting of dense sand over soft Bentonite clay.

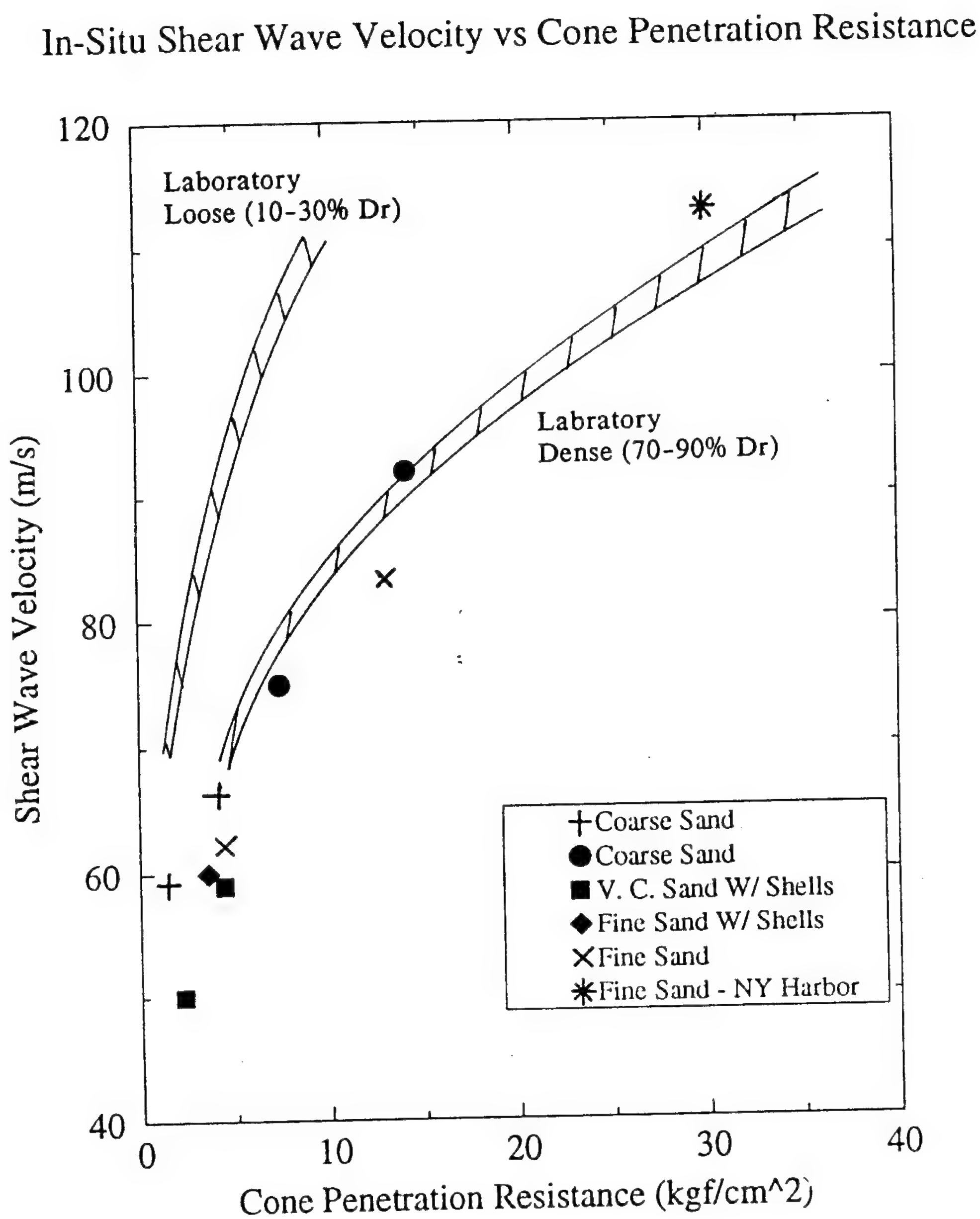


Fig. 7. Cone penetration resistance versus shear-wave velocity. All data from Gulf of Mexico near Panama City, Florida except asterisk which is from New York Harbor.

2.18 Characterization of Surfacial Roughness and Sub-Bottom Inhomogeneities from Seismic Data Analysis (Principal Investigators: D.J. Tang, G.V. Frisk and T.K. Stanton)

Characterization of Surfacial Roughness and Sub-Bottom Inhomogeneities from Seismic Data Analysis (Dajun Tang, George V. Frisk, and Timothy K. Stanton)

CBBLSRP FY94 YEAR-END REPORT

Dajun Tang, George V. Frisk, and Timothy K. Stanton
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

Summary of Work in This Period

This is the second year of the Coastal Benthic Boundary Layer Special Research Program. Last year two major experiments were successfully completed, one at the Eckernfoerde Bay near Kiel, Germany, the other at a coastal site neat Panama City, Florida. Our research during this year has been in the area of modeling and data analysis. Based on the experimental results, we collaborated with Darrell Jackson and Kevin Williams of the Applied Physics Laboratory, University of Washington and analyzed part of the data collected on their backscattering tower, the results are summarized in a paper entiled "Analyses of High-Frequency Bottom Backscattering for Two Distinct Shallow Water Environments", which will be published on the November, 1994 issue of the Journal of the Acoustical Society of America. Another paper addressing a technical issue in using the Differential Phase technique has been sent to the IEEE Journal of Ocean Engineering for review. Some of the data analysis results were also reported in the American Geophysical Union Ocean Sciences Meeting in San Diego, California. Recent modeling results will be presented this November at Austin, Texas, in the Acoustical Society of America bi-annual meeting. In order to verify and improve the model we have developed, we plan to analyze other data sets including bi-static scattering data and high-frequency normal incident data. The following is a summary of the results on data analysis and on the discussion associated with the application of differential phase technique.

Data Analysis of Backscattering

High frequency (40 KHz) bottom backscattering data obtained by the Benthic Acoustic Measurement System (BAMS), developed by APL, UW, from the two aforementioned shallow water locations were analyzed. The Eckernfoerde Bay site has a soft silty bottom, and the Panama City site has a hard sandy bottom. Since the data were recorded on two slightly separated arrays, the differential phase technique was used to locate the bottom scatterers at the two shallow water sites. The estimated average depth of bottom scatterers in the gas-rich soft sediments of Eckernfoerde Bay is about one meter below the seafloor, indicating that sub-bottom volume scattering is the dominant scattering source. In contrast the estimated scatterer depths in the sandy sediments of Panama City is about zero, i.e., at the water-sediment interface. Roughness scattering is believed to be the dominant scattering source at this sandy site, where further analysis is needed. However, one cannot exclude the possible importance of volume scattering immediately beneath the interface given the accuracy of depth estimation, which is in turn determined by the signal to noise ratio, sample size, and calibration accuracy of the system. In fact the estimated depth from the differential phase measurement represents the average depth, weighted by the contributions to the received signal, of scatterers insonified by the acoustic pulse.

If sediment volume scattering is dominant and the scatterers are homogeneously distributed in the sediment, the estimated scatterer depth will become smaller with decreasing grazing angle due to absorption loss in the sediments. Therefore, if the estimated depth of the volume scattering source is grazing angle independent, this implies the scatterers are distributed within a thin layer, such as for the case of the Eckernfoerde Bay site.

The processing of backscattering data for the Eckernfoerde Bay site shows the necessity of using the measured average grazing angle instead of the nominal grazing angle in estimating the array directivity effect. Otherwise the measured bottom backscattering strengths would give an anomalous grazing angle dependence. The standard deviation of estimated scatterer depths at the silty site is much greater than that at the sandy site, indicating also that volume scattering is dominant for the former.

The prediction of grazing angle dependence of the backscattering strength, based on a simple gas-bubble scattering layer, is consistent with the backscattering data, that is, the grazing angle dependence of backscattering is determined almost entirely by the grazing angle dependence of absorption in the sediment for the Eckernfoerde Bay site. Therefore, backscattering at higher frequencies would show stronger angle dependence than at lower frequencies. This can be tested using multiple frequency backscattering data. The backscattering strength in the gas-rich silty sediment is stronger than that in the sandy sediment. The model fit to the scattering data gives a level of gas-bubble layer scattering strength of about -10.8 dB. This should be further confirmed from the measurements of bubble size distribution and concentration.

Uncertainties of Differential Phase Estimation

The differential phase technique has been widely used in various sonar systems, however uncertainties associated with the estimation of scatterer depths are not completely understood. During the analysis of the BAMS data, this uncertainty became an issue which needed to be addressed. Numerical simulations for multiple bottom scatterers are performed and they show that the uncertainties of depth measurements in the absence of noise interferences are much greater than the amount explainable by the uncertainty associated with the signal-arrival-angle within an instantaneous insonified area. The cause of the excess deviation is analyzed particularly for the two-scatterer case. This kind of error source is referred to as "baseline decorrelation" which is related to the speckle phenomena and can be considered as an equivalent noise source. Since the Panama City is known to be flat, the backscattering data collected there are ideal to be used in model/data analysis. Both analytical formulas and numerical model are given to estimate the measurement uncertainty caused by the baseline decorrelation as well as noise interferences based on the parameters of the BAMS in order to understand uncertainties of the differential phase estimation. It is found that baseline decorrelation is the main error source for the BAMS for grazing angles greater than 12 degrees. The measurement uncertainties at this grazing angle interval are in agreement with the theoretical predictions.

Issues in Future Modeling

The major issues in modeling scattering by gas voids buried in the sediments are:

1. Is the gas scattering resonant?

2. Is the gas scattering directional? If so, how propagation effects will change such directivity?

3. Does a positive sound speed profile exist? If so, given the weak attenuation, how to cope with the multiple incidence/scattering process?

4. Did multiple scattering occur?

The major issues in modeling scattering by sandy bottoms are:

1. Is scattering caused by roughness alone or the layer of sediment immediately beneath the water/bottom interface has volumetric scattering contributions?

2. Is multiple scattering important?

In order to understand these questions, in addition to theoretical development, a key to success is to integrate acoustic data in many frequencies and other geometries along with sediment ground truth data. This will be a logical next step for the future.

List of Publications and Presentations for the First Two Years

1. Tang, D., G. Jin, D. Jackson, and K. Williams, "Analyses of high-frequency bottom and sub-bottom backscattering for two distinct shallow water environments," J. Acoust. Soc. Am. (In press)

2. Jin, G. and D. Tang, "Uncertainties of differential phase estimation associated with interferometric sonars," submitted to IEEE Journal of Ocean Engineering.

3. Tang, D., G. Jin, D. R. Jackson, and K. L. Williams, "Analyses of high-frequency bottom and sub-bottom backscattering for two distinct shallow water environments", American Geological Union Ocean Sciences Meeting, Feb. 1994, San Diego, CA.

4. Tang, D., "Modeling of high-frequency acoustic wave scattering by sediment gas voids," Acoust. Soc. Am. 128th Meeting, Austin, TX, Nov. 1994.

2.19 Quantification of High Frequency Acoustic Response to Seafloor Micromorphology in Shallow Water (Principal Investigators: D.J. Walter, D.N. Lambert, J.A. Hawkins, D.C. Young and J.C. Cranford)

Quantification of High Frequency Acoustic Response to Seafloor Micromorphology in Shallow Water

D.J. Walter, D.N. Lambert, J.A. Hawkins, D.C. Young,
Naval Research Laboratory, Code 7431, Stennis Space Center, MS 39529
and
J.C. Cranford,
Neptune Sciences, Inc., 150 Cleveland Ave., Slidell, LA 70458

PROJECT OBJECTIVES

The objectives of this project are to: (1) investigate new methods of quantifying the effect of sediment micromorphologic structure on high frequency acoustic response in shallow water and its relationship to in situ acoustic and geotechnical properties, and (2) provide 3-D digital high resolution micromorphologic characterization of the CBBL/JOBEX (southwest Baltic Sea) and other CBBL experimental sites .

CURRENT STATUS AND PROGRESS

NRL is utilizing a state-of-the-art, high frequency, high resolution acoustic system to characterize seafloor and sub-seafloor sediments with a dynamic range of greater than 92 dB. This high resolution Acoustic Seafloor Classification System (ASCS) presently uses a narrow beamwidth transducer (6° or 12°), is normally operated at 15 or 30 kHz, with a short pulse length (0.1 to 0.3 ms) and consists of a 16 bit data acquisition, processing, and display controller integrated into an 80486 microcomputer. A second integrated 80486 microcomputer processes the raw acoustic data into near real-time predictions of sediment physical and geotechnical properties and also generates a color screen map image of surficial sediment impedance along the survey trackline for use in making an initial assessment of the areal variability of seafloor sediment properties.

Two major field efforts were conducted (Dry Tortugas and Marquesas Keys areas off Key West, FL and Eckernfoerder, Germany) during FY94 using the NRL ASCS to support the objectives defined above and those of the overall CBBL Program. Three additional field efforts (two in Mississippi Sound and one in Chesapeake Bay), and three transducer testing and calibration efforts (two at Stennis Space Center, MS and one at the Applied Research Laboratory of the University of Texas at Austin), which supported CBBL objectives, were also conducted during FY94. The extensive acoustic data sets collected during the Key West and Eckernfoerder surveys were used to identify potential ground truth sampling and instrumentation deployment sites for the CBBL experiments.

FIELD EXPERIMENTS:

Key West Area: After conducting a widely spaced reconnaissance survey of the Dry Tortugas and Marquesas Keys areas (Fig. 1) two smaller areas were identified which were judged to be appropriate for the site selection requirements of the CBBL program. One site is located to the southeast of Fort Jefferson National Monument (Fig. 1, box a) and the other immediately to the north of the Marquesas Keys (Fig. 1, box b). A detailed series of acoustic surveys were conducted over each of these areas and core sample locations were selected based on data obtained during these surveys. The ASCS surveys were subsequently used to select the sites for the major FY95 CBBL field experiments.

Although bottom sediments in this region are composed almost entirely of carbonate materials, the overall variability of sediment types was interestingly diverse, ranging from carbonate reef rock and highly reflective sand deposits to relatively soft carbonate muds. The muddy sediments tend to be located in topographic lows and often contain varying percentages of carbonate shell and much evidence of bioturbation near the sediment-water interface. Throughout the region, the highly irregular undulating surface of the Key Largo limestone underlies the Holocene sediments deposited on the Florida Keys platform. The Key Largo limestone was formed as a reef deposit during the Pleistocene. Subsequently, it was aerially exposed and is characterized by a leached, karstic surface. Later transgression during the Holocene submerged it to it's present level. Of particular interest is the diversity and high variability in normal incidence sediment acoustic response that typifies the region. Although the exposed rock in the area would be expected to give the highest reflectivity values, surface roughness causes scatter which significantly degrades the intensity of the return signal. Sand deposits were often found to provide the highest reflectivities although prevalent sand waves with amplitudes as high as five meters caused a great deal of variability in the measurements. The soft sediments are surprisingly reflective when compared to terrigenous sediments. This is thought to be due to rapid dewatering below the sediment-water interface and the presence of carbonate shell materials near the sediment surface.

Kiel and Eckernfoerder Bays, Germany: ASCS data was obtained along numerous transects in the Kiel Bay/Eckernfoerder Bay area. All of the ASCS data within the test area was collected simultaneously with the FWG side scan sonar system. Much of the ASCS data collected outside of the CBBL test area was obtained in conjunction with the University College North Wales' (UCNW) Magic Carpet and Uniboom Systems. A significant volume of simultaneous ASCS data was also obtained while the following in-situ systems were recording data on station at the test area in Eckernfoerder Bay; NRL's ISSAMS, University of Hawaii's Acoustic Lance, NRL's Neptune, and NRL's buried hydrophones. Stationary ASCS acoustic data was collected at 25 gravity core and 20 box core stations throughout the region.

ASCS data collected in real time within and near the CBBL test area indicates that the surficial sediments within the test area are softer and less acoustically reflective than in other areas adjacent to the test area. Figure 2a is a color 30 kHz seismic record obtained in the CBBL test area at Core Site 320. A comparison of ASCS predicted properties from this data to ground truth core data at the same location is shown in Figure 2b. Good correlation is shown in this plot for the upper 50 cm of the sediment column. Below 50 cm, the sediment acoustic response is dominated by the presence of methane gas bubbles in the sediment. These bubbles cause a stronger acoustic reflection than would be expected if the sediment did not contain the bubbles. Because of this, the ASCS tends to predict a higher value of acoustic impedance than it should in gassy sediments. Therefore, the ASCS then predicts higher values of density and shear strength than it should. Similarly, impedance values determined from measurements on the core samples are low due to the slow compressional sound speeds (1000 - 1200 m/s) measured by the core scanner in the gassy sediments. This problem is not surprising and a solution is being sought through the use of techniques that would allow the automated recognition of gassy sediment from the acoustic response.

In another comparison, ASCS data collected along a transect that runs between the Mittelgrund and Stollergrund bathymetric highs (Fig. 3a) correlates well with the ISSAMS in-situ measurements of sediment compressional and shear wave velocity data as well as sediment physical and geoacoustical property data obtained from gravity and box cores along the same line. Figure 3b is an example plot of ASCS predicted data compared to core data collected at Core Site 658 and ISSAMS Site 670. A reasonable correlation is shown for porosity and compressional velocity at this site. Real-time correlation between the ASCS data and that obtained by the UCNW Magic Carpet and Uniboom systems was also observed (A. Davis and D. Huws, personal communication) during the coordinated tows where both systems were operated simultaneously. Additional ASCS and ground truth data comparisons were presented at the 128th meeting of the Acoustical Society of America and at the International Conference on Underwater Acoustics at the University of South Wales, Australia.

Mississippi Sound: Two field tests were conducted (April and September) within the Ship Island Testbed in Mississippi Sound. Although this field work was conducted primarily to address goals of the Naval Facilities Engineering Service Center's (NFESC) Acoustic Validation Project, it also provided important field engineering test time for validation of a new ASCS data acquisition system prior to it's shipment to Germany for use during the CBBL Eckernfoerder studies in June and July. The testbed area provides easy access and contains a variety of sediments ranging from hard, moderately well packed quartz sands to soft, silty clay mud deposits which overly a relict Pleistocene quartz sand formation. The test area covers a 3 by 6 nm area that has eight extensively sampled ground truth core locations. Although this work was not sponsored by the CBBL, it is mentioned here because the goals of the project compliment those of the CBBL and can provide additional insight into the quantification of the acoustic response of various sediments.

The objective of the NFESC project is to compare acoustic sediment property predictions, particularly shear strength, to those measured in situ using standard geotechnical tools. These measurements are being made within a variety of sediment types in four different geographic regions Mississippi Sound, Chesapeake Bay, Key West area, and off the California Coast. ASCS predictions of sediment strength are being compared with sediment strength measurements obtained using a SEAfloor Piezometric Cone Penetrometer System (SEAPCONE), an Expendable Doppler Penetrometer (XDP) System, a Rapid Geotechnical Survey Tool (RGST), and ground truth sediment cores. NFESC will be participating during the February (95) Key West/Dry Tortugas joint field efforts, making this additional data set available to interested CBBL, MTEDS and TTCP investigators.

Chesapeake Bay: Another NFESC funded field effort, with the same objectives as those identified above, was conducted during August and September, 1994 that covered a significant portion of Chesapeake Bay. This effort was also supported financially by NRL Codes 7400 and 7420. In addition, the Maryland Department of Natural Resources, Geological Survey and Fisheries Division each provided a vessel for a total of 20 operational days to conduct this work. One other NRL scientist, Dr. Peter Vogt/Code 7420, participated in this effort to study Holocene sedimentation within paleochannels and depositional patterns on the bay bottom to evaluate ongoing cliff erosion from Calvert Cliffs of Maryland. Three scientists from the State of Maryland also participated to study; a) the bearing capacity of the seafloor for selecting artificial oyster reef planting sites, b) the location and distribution of gas in Holocene paleochannels, and c) acoustic detection of oyster bar material and prediction of shell densities and sediment type distribution within the bar vicinity.

A total of nine sites were acoustically surveyed with ten additional acoustic transects being conducted along selected portions of the bay. Of the nine sites, five were subsequently sampled using the SEAPCONE, XDP, RGST, and sediment cores. All but one of these sites were located in the western, shallow coastal areas of the bay, and ranged from about 38° 05' to 38° 46' N. Latitude. One site in the waters of the Maryland Eastern Shore (Cook Point in the Choptank River), was also fully surveyed and sampled similarly to the other sites.

Many portions of the surveyed regions north of the Patuxent River and within the main stem of the bay and westward of it are populated with sediment filled, abandoned remnants of Susquehanna River paleochannels. Biogenic gas was observed on many acoustic tracks over these paleochannels. The presence of gassy sediments appears to be a common feature in many of the fine grained sediments encountered in Chesapeake Bay and Mississippi Sound, making these ideal regions for conducting further studies of gassy, shallow water, marine sediments. These extensive data sets also compliment those collected in the Baltic Sea for the CBBL project and are available to CBBL participants.

TRANSDUCER TESTING AND CALIBRATION: Three system calibration studies were conducted in water tanks during FY 94. Two of these were conducted at the National Marine Fisheries Service (NMFS) test tank at Stennis Space Center. The other tests were completed at three locations at the Applied Research Laboratory of the University of Texas at Austin (two tanks on the ARL campus and another in the calibration facility at the Lake Travis test area). The primary thrust of these tests was to measure the frequency response and perform sensitivity analyses on the various transducers used with ASCS, particularly those used in the CBBL studies.

During one test, the transducers were suspended upside down in a tank and focused at the air-water interface. This exercise was intended to measure the transmit and receive response (except for a negative unity reflectivity for the air-water reflection) of the transducer for specific pulses. This test resulted in the observation of a range of behavior among the transducers. In some cases, the pulse length of the source signal was longer in the water than the source fire signal, particularly when attempting to fire the transducers at less than 0.3 ms. The EDO 15 kHz transducer exhibited a pronounced ringing over a wide band of frequencies when it was fired at 30 kHz. This resulted in an apparent longer and wider bandwidth pulse in the water than expected. Although this observation would indicate that the temporal resolution was less than had been previously indicated, the wide bandwidth provided an opportunity to attempt a more robust calculation of sediment response using a deconvolution algorithm.

Signal Processing: Figure 4 shows the reflected signal obtained from the bottom of a wooden tank during transducer testing at ARL/UT (Austin, TX). The reflection off the bottom is observed at about 0.1 ms. Inspection of the deconvolved signal (Fig. 5), provides both a sharper definition of the bottom return and a better view of a second reflecting surface at 0.05 ms below the tank bottom. The presence of subbottom reflectors is consistent with construction diagrams of the bottom of the tank, which consists of an air-filled honeycomb of wooden timbers on top of a carbonate rock floor. This hypothesis is necessarily qualitative because the specific location of the transducer with respect to the timber framework could not be determined. However, regardless of the exact construction of the tank, the deconvolution produced better resolution than the unprocessed return.

Based on the results from this increased bandwidth analysis, the use of a 30 $\rightarrow$ 15 kHz linear frequency sweep pulsed transmission was investigated. The sweep signal pulse was studied in the NMFS test tank and determined to be suitable for further evaluation during field tests in Mississippi Sound. The increased bandwidth yielded still greater improvement in measuring the acoustic reflectivity with the deconvolution algorithm. Figure 6 shows a series of acoustic pings taken along a track in Mississippi Sound near Ship Island, MS. The source used for these pings was a 30 kHz signal with a pulse length of 0.2 ms. Figure 7 shows a series of pings along the same trackline using a 1.0 ms, 30 $\rightarrow$ 15 kHz linear sweep source signal with the same transducer. These returns were deconvolved to yield this record. The compression in time of reflecting surfaces (and consequently spatial resolution) gained by deconvolution is clearly greater than that obtained using the short pulse source. These results demonstrate that the implementation of this deconvolution algorithm into the signal processing string can improve the resolution of the reflectivity sequence over the existing ASCS inversion algorithm technique. The results from this

investigation were presented at the 128th meeting of the Acoustical Society of America in Austin, Texas in November, 1994.

ASCS Impedance Algorithm: The accurate determination of the reflectivity sequence is important primarily for imaging reflecting horizons within the acoustically sampled sediment column. While this is important, the determination of impedance requires further analysis. Evaluation of the current ASCS impedance inversion algorithm has continued during this reporting period. This analysis indicates that while successful in most sediment regimes, it nevertheless makes broad assumptions about the acoustic signal and it's interaction with the sediment volume which could lead to sometimes ambiguous and occasionally inaccurate impedance estimates. A linear inversion, implemented by Warren Wood of NRL has been used with the raw, unprocessed ASCS acoustic return to estimate impedance. The acoustic record coupled with trend estimates from core data is input to a linear inversion algorithm (similar to the deconvolution algorithm described above) to determine impedance. The resulting impedance calculations show good agreement with the core analyses.

GAS BUBBLES IN MARINE SEDIMENTS: Acoustic effects due to the presence of bubbles in the sediment have been shown to be very pronounced, particularly in the sediments important to the study of the benthic boundary layer. Analysis continued on the Eckernfoerder Test Site gassy sediments. ASCS measurements made there during the 1993 field work were presented in a poster at the Gassy Mud Workshop in Kiel, Germany in July, 1994. The observation of gaseous sediments in Mississippi Sound and Chesapeake Bay indicates that gaseous sediments are a common feature in many coastal estuarine environments. These gaseous sediments impart an uncharacteristic and unpredictable impediment to the propagation of acoustic energy within the sediment volume. Therefore, developing an understanding of the mechanisms which result in their occurrence and a method to model their affect on acoustic propagation are important considerations for further study and understanding when considering the likelihood of conducting naval operations in coastal/estuarine areas around the globe.

A model for bubbly sediments has been developed by A. Lyons and A. Anderson of Texas A & M University, in which bubbles are assumed to be discrete scatterers imbedded in a homogeneous, or slowly varying medium. In collaboration with these investigators, we have constructed a series of synthetic returns from calibrated ASCS sources and bubbly sediment parameters from core data collected in the Eckernfoerder pock mark area. The synthetic returns show good qualitative agreement with actual ASCS returns. Preliminary results of this data were presented at the 128th meeting of the Acoustical Society of America in Austin, Texas in November, 1994.

SUMMARY

The work described in this report contributes to the CBBL SRP in three significant ways. First, the ASCS raw data provides an important addition to the databases of acoustic information on sediments important to the CBBL SRP. To this end, we have collected data during FY94 from four regions, Eckernfoerder/Kiel Bays, the Florida Keys, Mississippi Sound, and Chesapeake Bay. These shallow bay and key coastal areas contain a variety of sediment types including highly reflective sands, homogeneous and layered (sand/mud) areas, highly variable carbonate sediments, and very low viscosity muds with gas bubbles. Second, the ASCS records and data were used extensively for determining the best locations, both in the Baltic Sea and in the Florida Keys, to conduct the extensive CBBL measurements. The success of the CBBL experiments, to date, testify to the importance of the ASCS for the location and characterization of the specific test sites. A third contribution is the use of the ASCS data in the development of models of the acoustic response of these sediments and the extent which they can be characterized by their response. The model developed by Texas A&M and NRL of the acoustic response of gassy sediments is a prime example. ASCS data has also been provided to a number of other investigators participating in the CBBL SRP.

PUBLICATIONS AND PRESENTATIONS

D.N. Lambert, J.C. Cranford, D.J. Walter, J.A. Hawkins, and R.D. Redell, "Geological characterization of Kiel and Eckernfoerder Bay sediments using a high resolution remote acoustic seafloor classification system," AGU 1994 Ocean Sciences Meeting, EOS, Vol. 75 (3), 160, Jan. 1994.

D.N. Lambert, D.J. Walter, W.R. Bryant, N.C. Slowey, and J.C. Cranford, "Acoustic prediction of sediment impedance," J. Acoust. Soc. Am. 96, No. 5, Pt. 2, 3222 (A) (1994).

D.N. Lambert, D.J. Walter, D.C. Young, M.D. Richardson, and J.C. Cranford, "High resolution acoustic seafloor classification system for mine countermeasures operations," Proc. Int. Conf. on Underwater Acoustics, Univ. of South Wales, Australia, 67-69 (1994).

M.D. Richardson, D.N. Lambert, K.B. Briggs, and D.J. Walter, "Comparison of acoustic seafloor classifications (ASCS) and in-situ geoacoustic (ISSAMS) data collected from a variety of sediment types in Kiel Bay, Germany," Proc. Int. Conf. on Underwater Acoustics, Univ. of South Wales, Australia, 89-90 (1994).

A.P. Lyons, M.E. Duncan, J.A. Hawkins, Jr., and A.L. Anderson, "Predictions of the acoustic response of free-methane bubbles in muddy sediments, "J. Acoust. Soc. Am. 96, No. 5, Pt. 2, 3217 (A) (1994).

J.A. Hawkins, W.T. Wood, D.N. Lambert, and D.J. Walter, "The characterization of near-surface sediments with high-frequency acoustic pulses," J. Acoust. Soc. Am. 96, No. 5, Pt. 2, 3223 (A) (1994).

J.A. Hawkins, D.N. Lambert, D.J. Walter, and J.C. Cranford, "Observations of acoustic reflectivity associated with near-surface (shallow subbottom) gassy sediments in Kiel and Eckernfoerder Bays", AGU 1994 Ocean Sciences Meeting, EOS, Vol. 75 (3), 159, Jan. 1994.

J.A. Hawkins, D.N. Lambert, D.J. Walter, and J.C. Cranford, "Acoustic imaging of near-surface bubbly sediments," Proc. Gassy Mud Workshop, Kiel, Germany. 54-58 (1994).

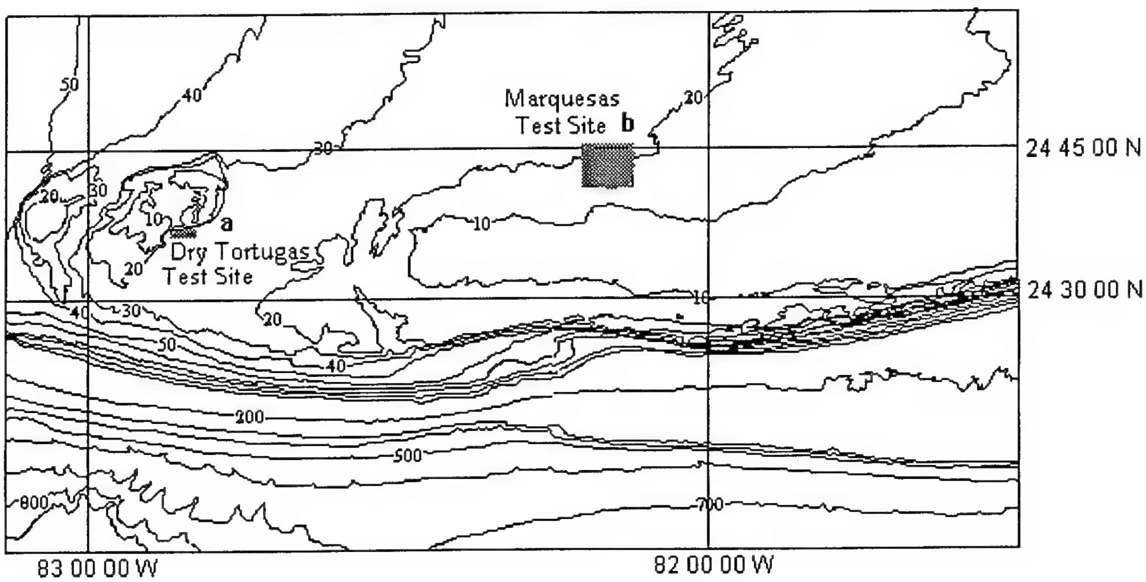


Figure 1. Bathymetric contour map showing location of selected CBBL test areas (gray) where detailed acoustic surveys were conducted near (a) Dry Tortugas and (b) Marquesas.

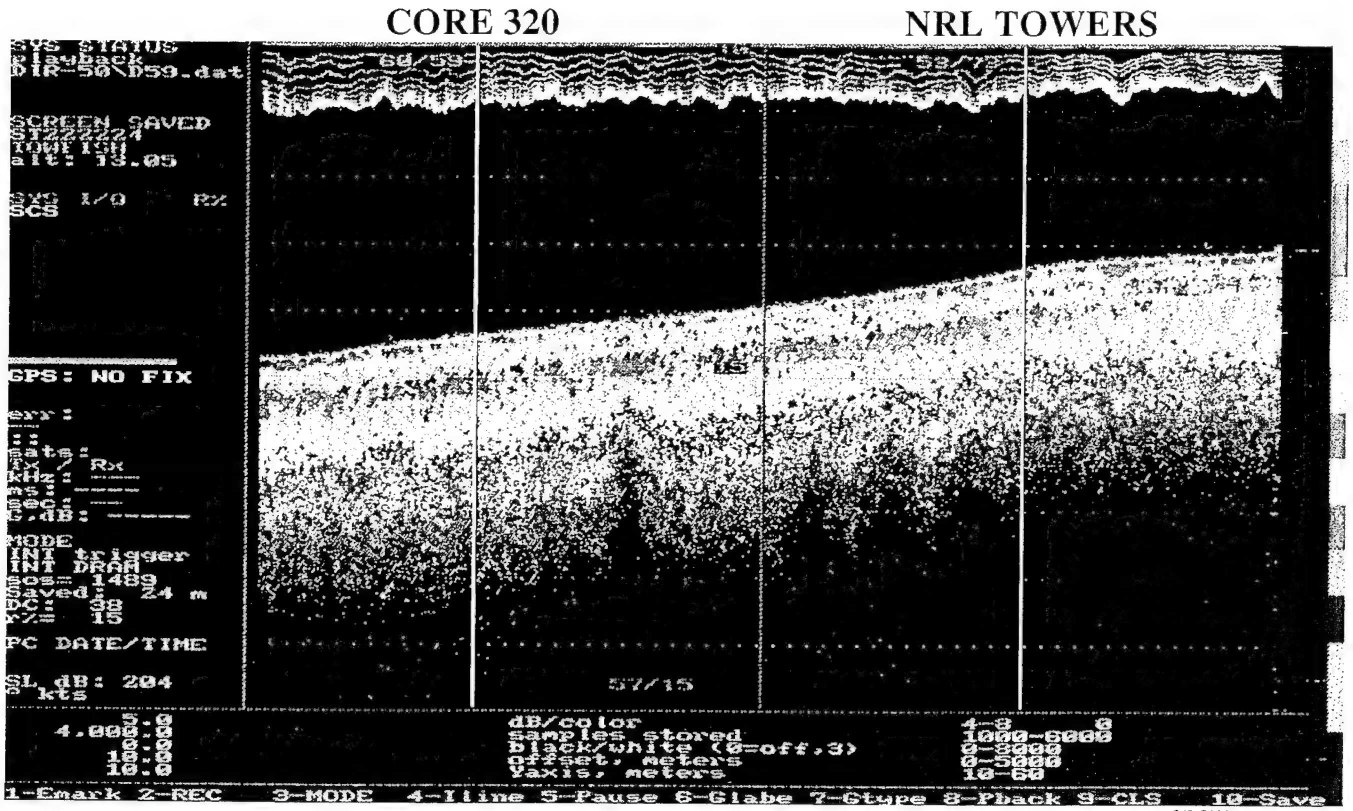


Figure 2a. 30 kHz ASCS trackline across the CBBL experiment site along Line I showing the location of Core 320 and NRL's backscatter and forwardscatter towers.

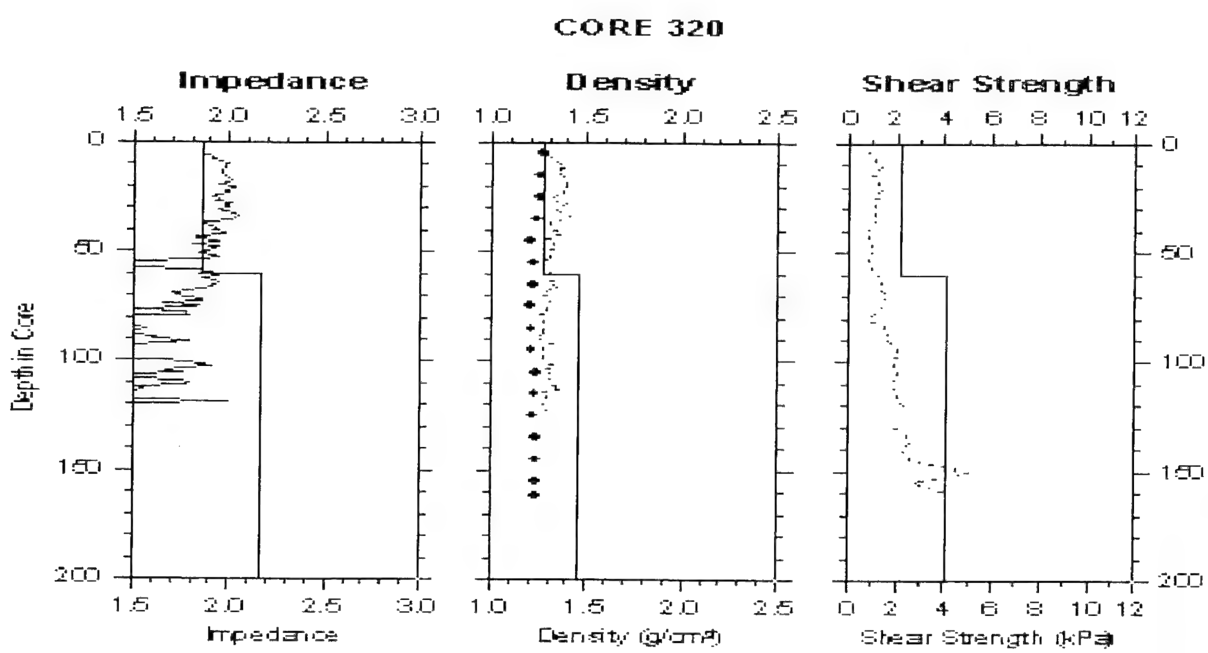


Figure 2b. Comparison of ASCS predicted sediment impedance, density, and shear strength (solid vertical lines) with ground truth sediment core data (jagged and dotted lines) for core 320.

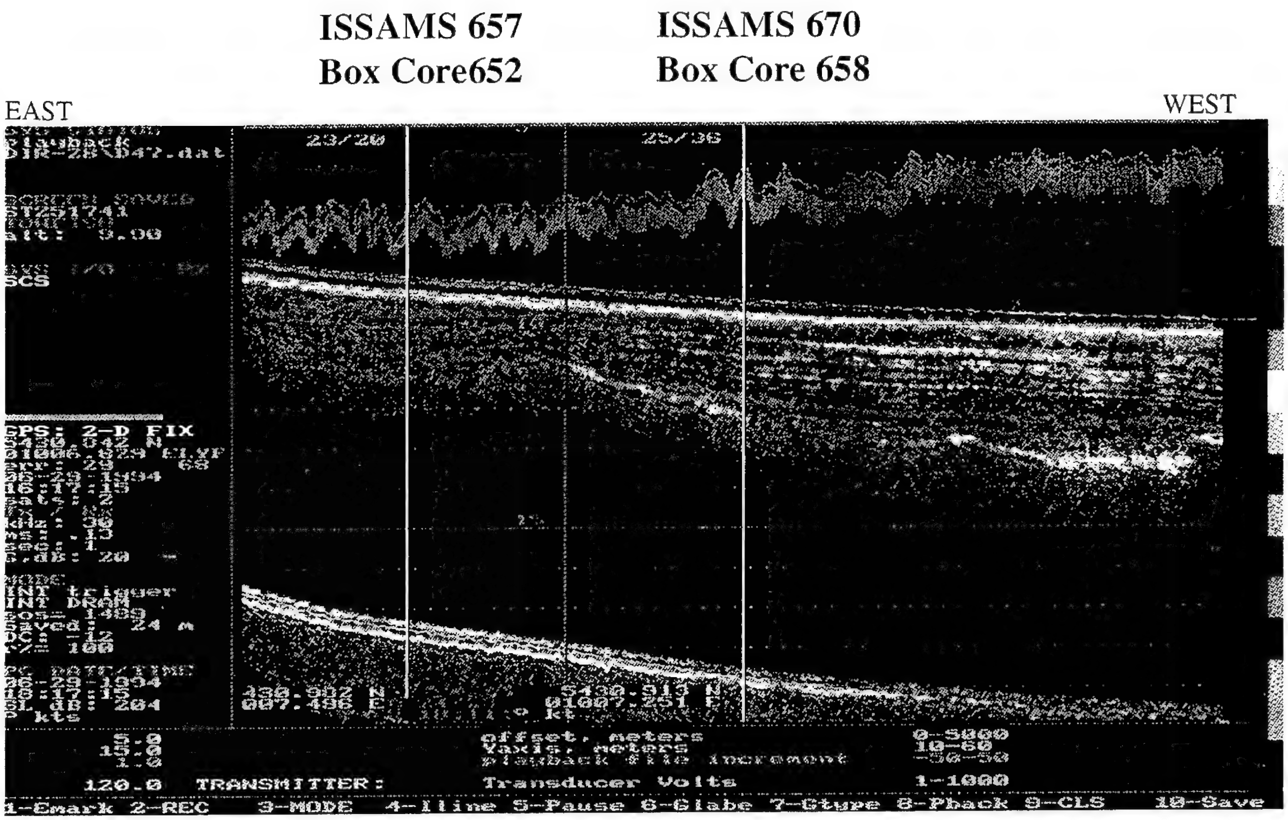


Figure 3a. ASCS 30 kHz seismic record across Line 47 showing the location of Core Site 658 and ISSAMS Site 670 in Eckernfoerder Bay, Germany

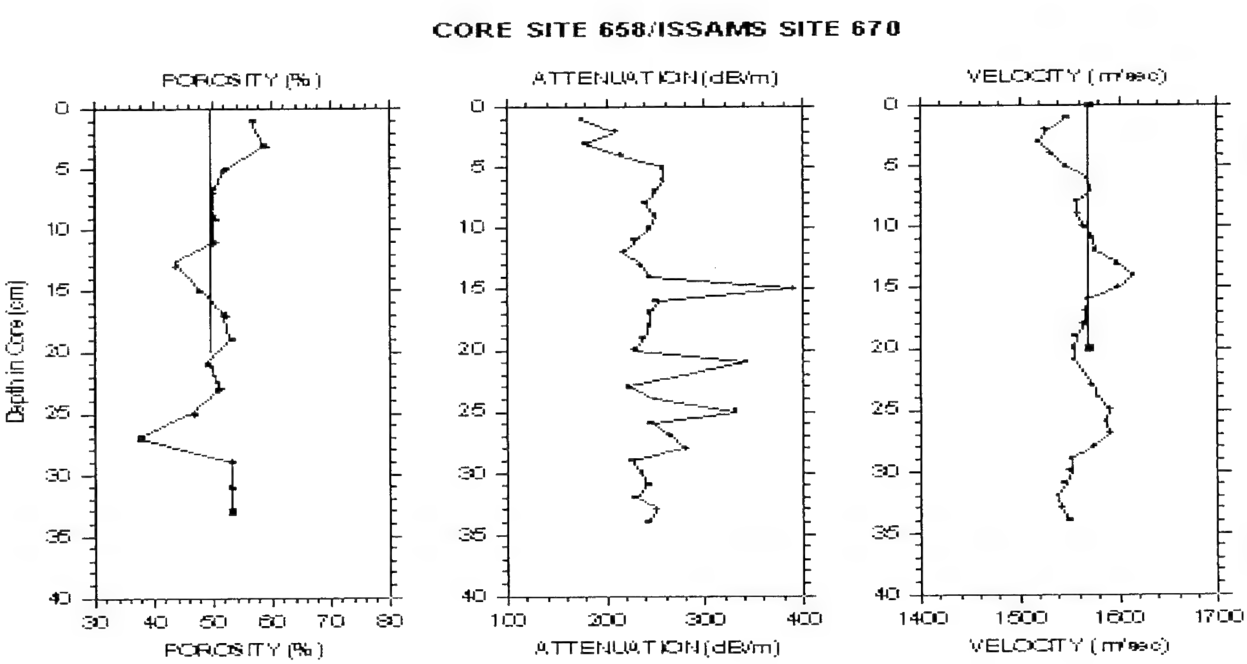


Figure 3b. Comparison of ASCS predicted sediment porosity and compressional velocity (solid vertical lines) with ground truth sediment core data (jagged lines) for core 320.

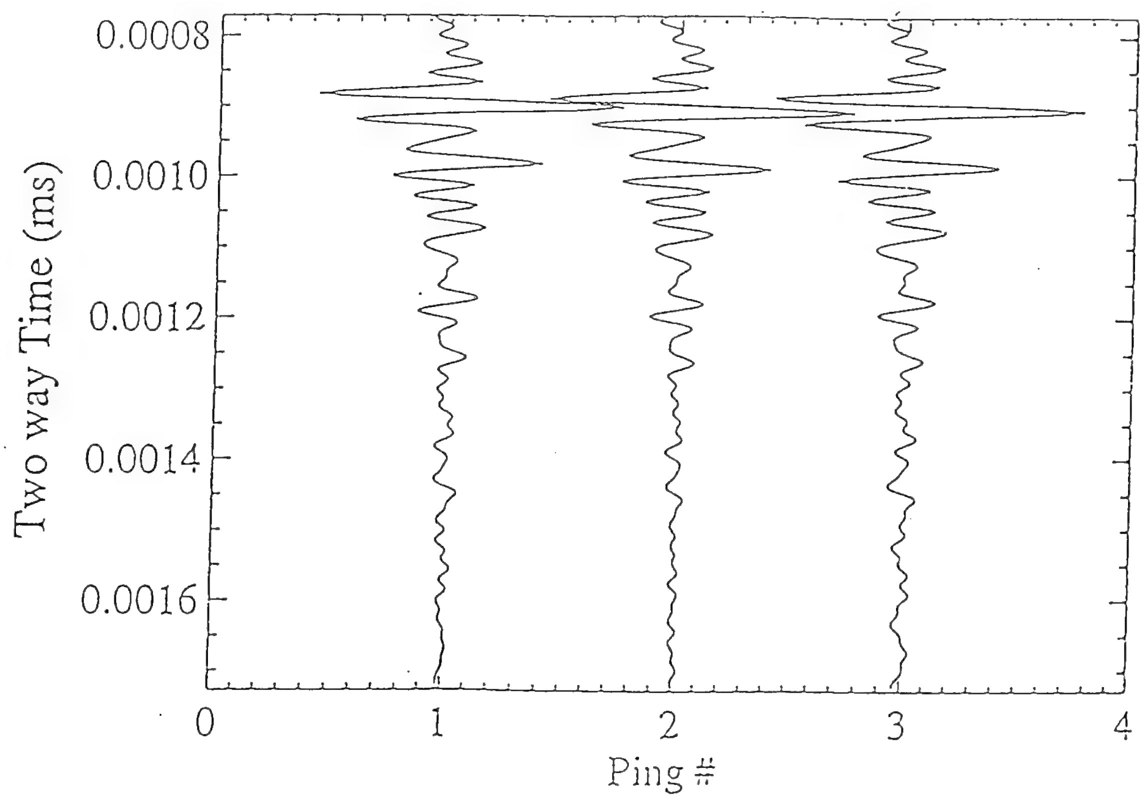


Figure 4: Three raw returns collected from the ARL/UT (Austin) wooden test tank.

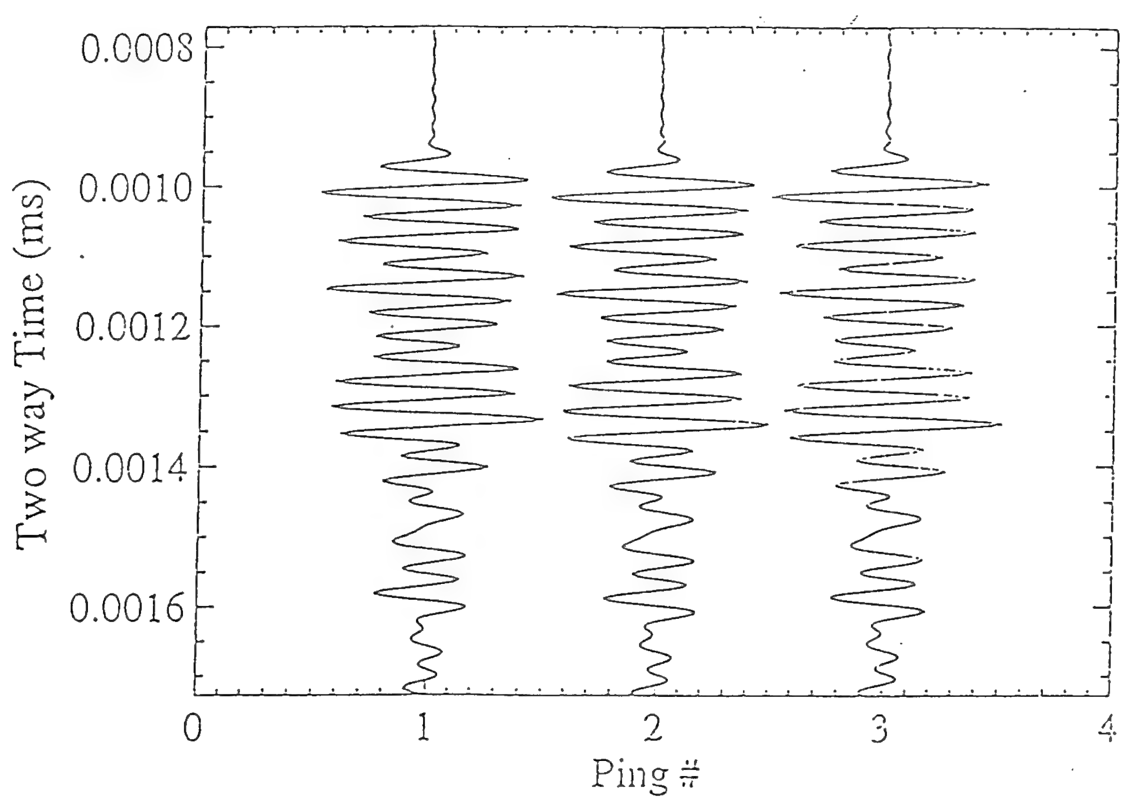


Figure: 5 The acoustic returns shown in Fig. 4 after deconvolution.

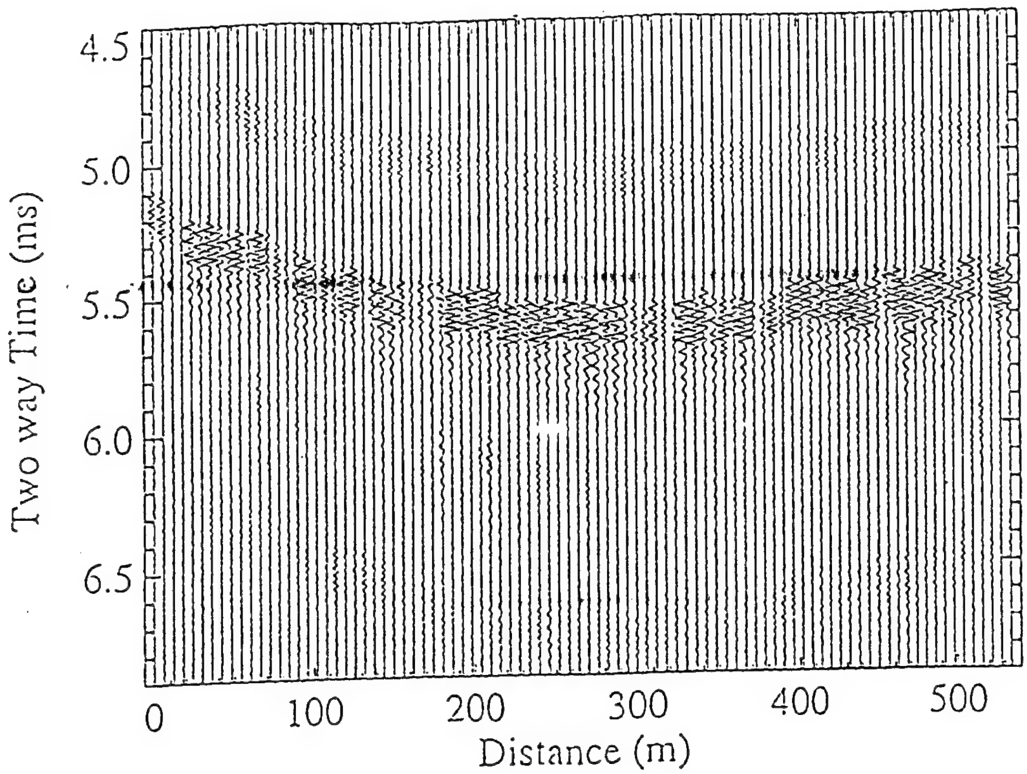


Figure 6: Acoustic record taken with a .2 msec, 30 kHz source over a shallow trough with a buried sand layer..

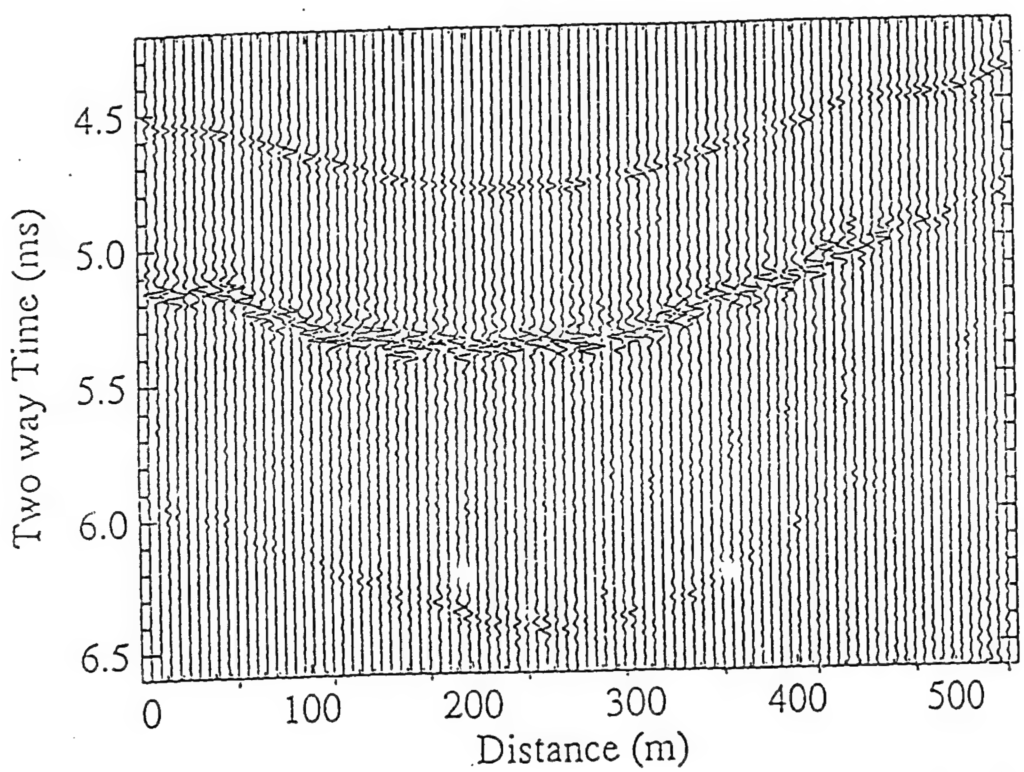


Figure: 7 Acoustic record made with a deconvolved 1.0 msec, 30--15 kHz sweep over the same region as that shown in Fig. 6.

2.20 Acoustic Lance Operations in Eckernförde Bay, 1994 (Principal Investigators: R.H. Wilkens, S.S. Fu and L.N. Frazer)

Acoustic Lance Operations in Eckernfoerde Bay, 1994

CBBL FY94 YEAR-END REPORT

R.H. Wilkens, S.S. Fu, L.N. Frazer
School of Ocean and Earth Science and Technology
University of Hawaii
Honolulu, HI 96822

Introduction

During the June-July, 1994, experiment in Eckernfoerde Bay the Acoustic Lance was deployed for the first time as part of the Coastal Benthic Boundary Layer Experiment. We provide here compressional wave velocity profiles for 18 stations based on a preliminary analysis of waveform first arrivals.

The Instrument

The Acoustic Lance is a linear array of receivers embedded in the seafloor below an acoustic source. It provides in situ recording of waveforms above and below the sediment-seawater interface. A broad-band acoustic source and a solid state data recording system are mounted on the weightstand of a gravity corer. An array of small hydrophones are mounted along the outside of the core barrel (nominally at 60 cm intervals in this experiment). This is the measuring geometry that has been used for many years to obtain thermal gradients in the seafloor, with temperature probes in place of hydrophones (Figure 1 - Top). An example of received waveforms from a calibration shot in seawater is shown in Figure 1 - Bottom.

A block diagram of the Lance electronics package is shown in Figure 2. A single pulse is simultaneously recorded at up to 10 receivers in the full package (eight receivers were deployed during this experiment). Each receiver card has an independent preamplifier, gain control (8 settings), anti-aliasing filter, 12 bit A/D converter, and 64k x 8 bit CMOS RAM. Currently we record at 10 msec intervals (100 kHz), allowing for storage of up to 300 msec of waveform data and attendant bookkeeping such as gain or delay settings. We also have the option of stacking and averaging up to 16 signals as they are recorded, to increase signal-to-noise ratio. Data are extracted by interrogating a serial port through an external connector. Data are read from RAM into an IBM Compatible PC for processing.

Receivers are standard Benthos AQ-1 piezoelectric hydrophone cartridges. The AQ-1's are ideal for Lance because they are small (1.6 cm diameter, 4.5 cm length), will withstand high pressures, have the proper frequency range (1 Hz - 20 kHz), and are relatively inexpensive (approximately $70 per element). Our source is a standard 2.5" x 5" OAS Inc. #E-2PD deep water hydrophone An SCR capacitive discharge pulse generator provides a signal with a distinct first arrival. A low power inverter supplies 800 volts DC to the pulse generator.

Results

During the 1994 Eckernfoerde experiment the Acoustic Lance was deployed at 18 stations during gravity coring operations and recorded a signal from the ASCS at one site. Typical waveforms recorded in water, gassy, and non-gassy sediments are displayed in Figure 3. There are two first-order observations to be made from these data; 1. Attenuation in the non-gassy sediments is pretty low (compare the relative signal loss with that of water in Figure 3.), and 2. Waveforms are an excellent indicator of the position of the attenuating gassy layer in the subsurface.

In situ velocity profiles of 5 stations (#624-#628) along a TAMU transect are displayed in Figure 4. Preliminary results from all stations are listed in Table 1. Compressional wave velocity of the non-gassy sediments in Eckernfoerde Bay does not display much vertical or lateral variability, overlying either gassy zones or hard bottoms. In general, compressional wave velocity values in non-gassy sediments fall inside the range 1430 m/s to 1465 m/s. Gassy sediments, in contrast, exhibit a large range. Although first arrivals are sometimes difficult to pick due to severe attenuation in gas layers, data indicate velocities from 1200 m/s to 900 m/s. Indeed, there are suggestions in the data that velocity may drop as low as 750 m/s within some intervals.

Velocity gradients vary within the upper several meters of seafloor in Eckernfoerde Bay. In non-gassy sediments velocities are more-or-less constant with depth (i.e. STN#624) or have an tendency to increase slightly (i.e. STN#627) over the upper 4 m of the seafloor. At gassy sites, velocities seem to maintain a similar profile to non-gassy sites over the upper meter or so, and then decrease more or less rapidly, depending most likely on the vertical distribution of gas bubbles.

Although there is a large drop in velocity within the gas zone, there is no apparent reflection signal from the gassy sediments recorded. Lance data do not show a strong acoustic reflection. This must be some effect of the

high attenuation of the gassy layer, suggesting that the gassy sediments are a strong acoustic absorption layer.

Summary

Acoustic Lance data provide in situ measurement of the compressional wave velocity within gassy sediments of Eckernfoerde Bay. These velocities may be as low as 750 m/s. In spite of the drastic velocity decrease, the gassy layers do not appear to be efficient reflectors, acting instead as energy absorbers.

In Situ Velocity Data from Eckernfoerde Bay

STN #624		STN #625		STN #626		STN #627		STN #628	
Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)
0	1480	0	1480	0	1480	0	1480	0	1480
0.46	1430	0.46	1419	0.46	1430	0.46	1430	0.46	1442
1.06	1439	1.06	1447	1.06	1473	1.06	1447	1.06	1447
1.65	1428	1.65	1455	1.65	1455	1.65	1428	1.65	1428
2.27	1446	2.27	1489	2.27	1526	2.27	1446	2.27	1446
2.87	1429	2.87		2.87	1482	2.87	1447	2.87	1439
3.47	1444	3.47	1169 *	3.47	1418	3.47	1453	3.47	1461
4.07	1442	4.07	852 *	4.07	n	4.07	1460	4.07	965 *

STN #639		STN #640		STN #641		STN #647		STN #649	
Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)
0	1480	0	1480	0	1480	0	1480	0	1480
0.46	1453	0.46	1442	0.46	1464	0.46	1464	0.46	1442
1.06	1482	1.06	1466	1.06	1492	1.06	1464	1.06	1438
1.65	1128 *	1.65	1112 *	1.65	986 *	1.65	1464	1.65	1464
2.27	1096 *	2.27	n	2.27	956 *	2.27	1179 *	2.27	1316 *
2.87	n	2.87	n	2.87	n	2.87	n	2.87	750 *
3.47		3.47	n	3.47	n	3.47	n	3.47	n
4.07	887 *	4.07	n	4.07	n	4.07	n	4.07	n

STN #653		STN #664		STN #665		STN #666		STN #667	
Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)
0	1480	0	1480	0	1480	0	1480	0	1480
0.46	1464	0.46	1476	0.46	1476	0.46	1488	0.46	1464
1.06	1421	1.06	1476	1.06	1467	1.06	1476	1.06	1407
1.65	1437	1.65	1479	1.65	1470	1.65	1470	1.65	1417
2.27	756 *	2.27	1471	2.27	1454	2.27	1507	2.27	1413
2.87	n	2.87	1464	2.87	1429	2.87		2.87	1412
3.47	n	3.47	1444	3.47	1444	3.47	1445	3.47	1427
4.07	n	4.07	1433	4.07	1442	4.07	1425	4.07	1425

STN #668		STN #673		STN #613_A		STN #613_B		STN	
Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)	Depth (mbsf)	Velocity (m/s)
0	1480	0	1480	0	1480	0	1480		
0.46	1442	0.46	1464	0.46	1430 ?	0.46	1464		
1.06	1423	1.06	1424	1.06	1511	1.06	1511		
1.65	1425	1.65	1062 *	1.65	n	1.65	1446		
2.27	1429	2.27		2.27	n	2.27	n		
2.87	1412	2.87		2.87	n	2.87	n		
3.47	1418	3.47		3.47	n	3.47	n		
4.07	1392	4.07	1072 *	4.07	n	4.07	n		

*: velocities of gassy sediments, the first arrival would be interfered by noise.
n: no data, because there is no recognizable first arrival.
?: first arrival was distorted.
Shading cell: to every set data, if there is a shading cell it means the mud line starts at this depth (mbsf). If there is no shading cell, it means mud line starts at 0 mbsf.
Velocities at 0 mbsf are averaged bottom water velocity.

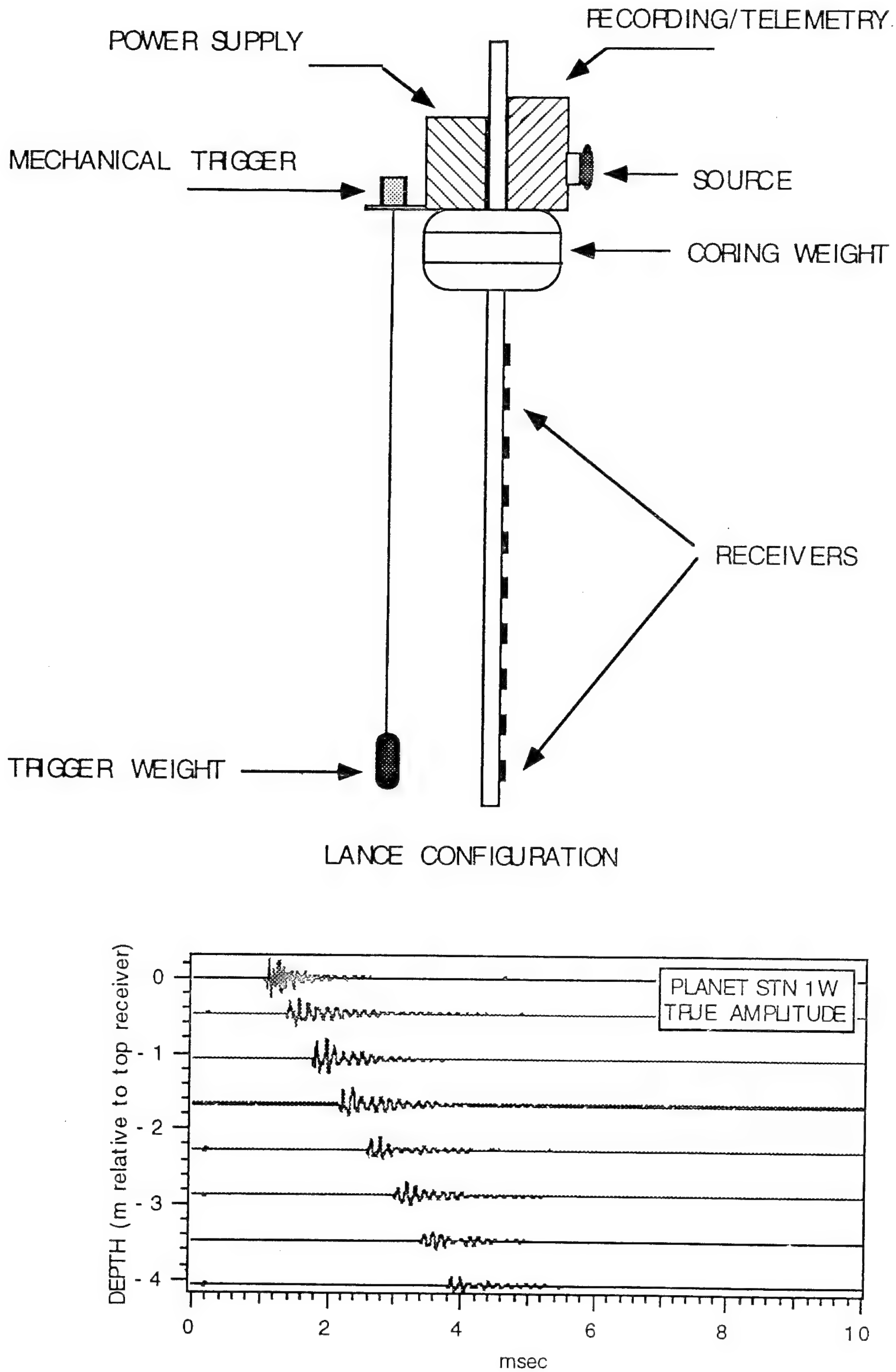


Figure 1. Lance configuration and results of water calibration shot.

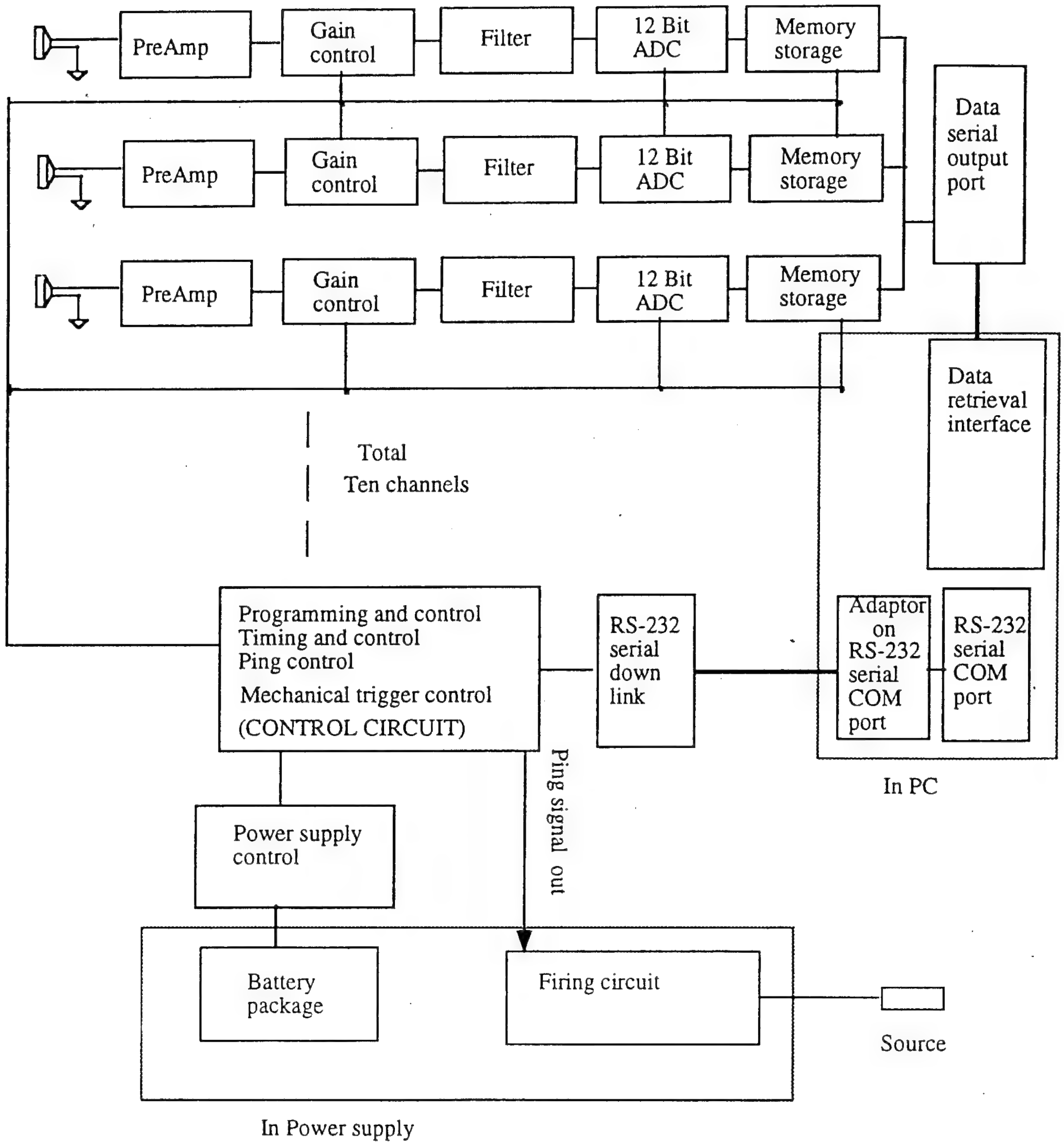
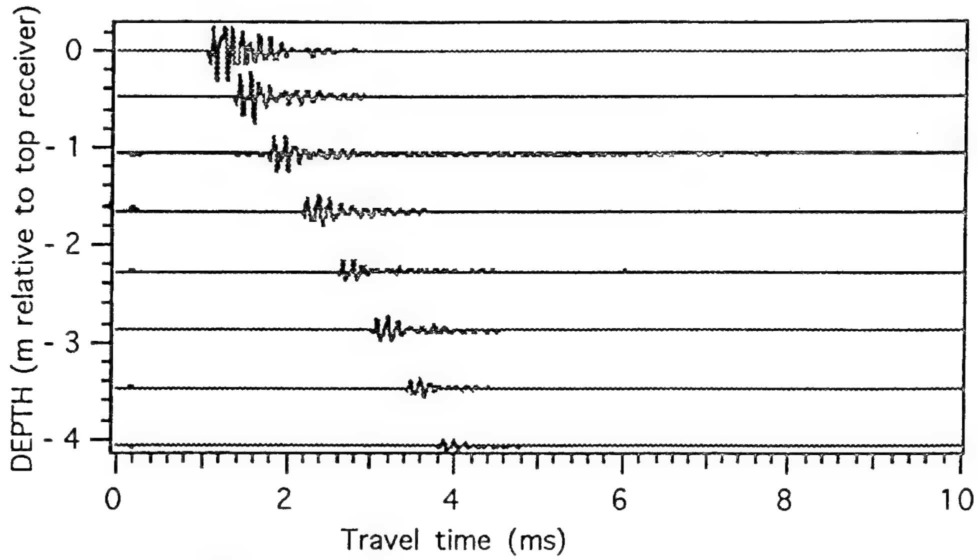
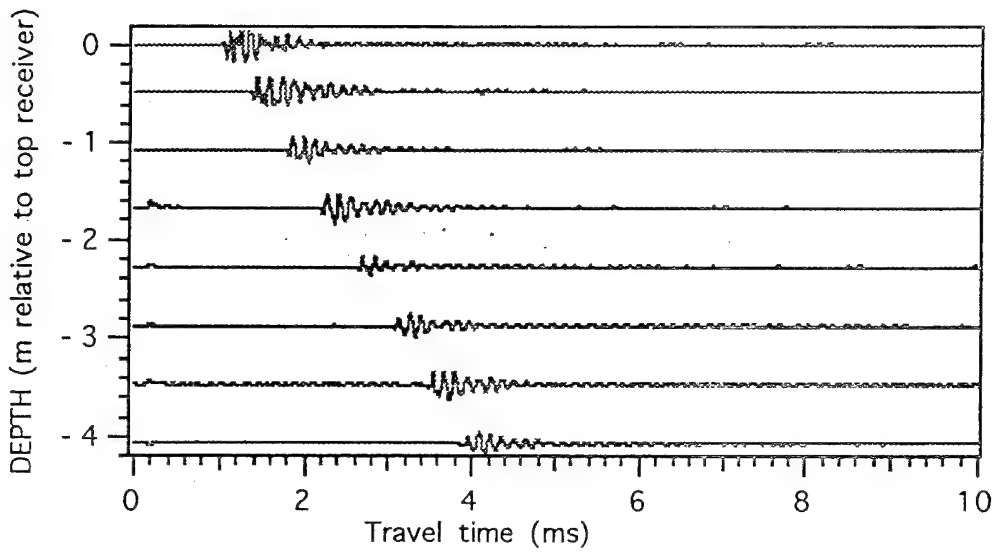


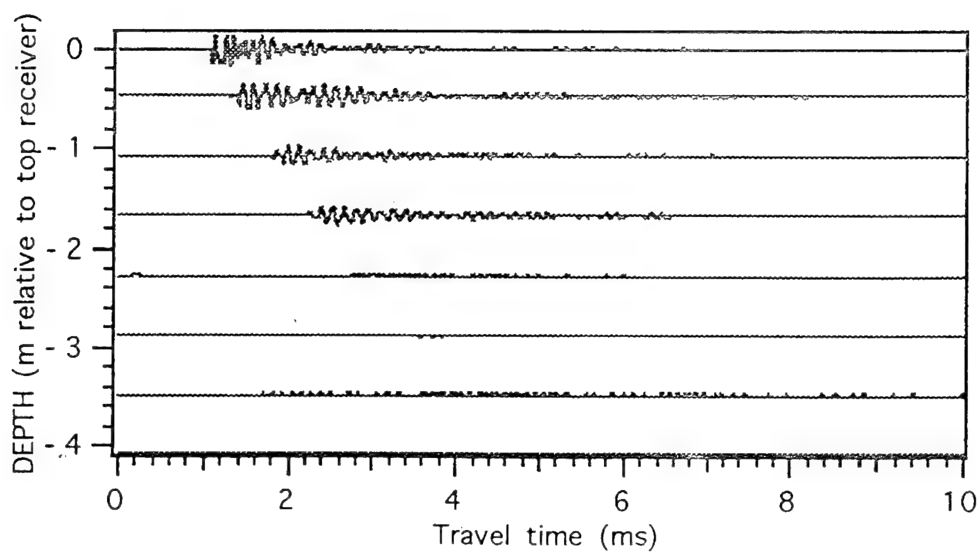
Figure 2. **Block Diagram of Electronics of Lance**



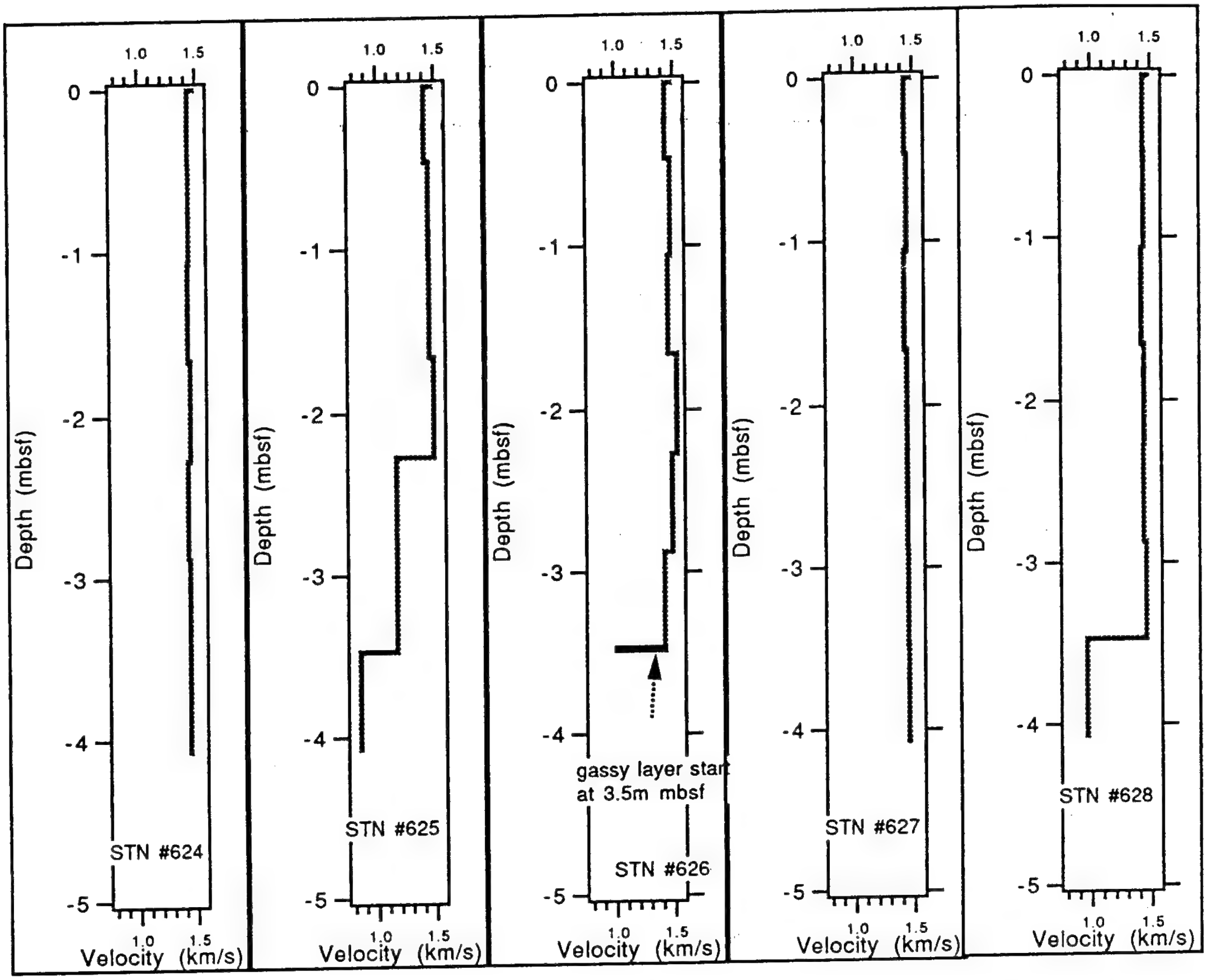
Siganls received in water (normalized amplitude)



Signals received in non-gassy sediments (STN #624, normalized)



Signals received in gassy sediments (STN #625, normalized).
Gassy layer start at 2.2 mbsf.



Velocity profiles of Station #624 - #628.

2.21 Observation of Bottom Boundary Layer Hydrodynamics and Sediment Dynamics in Eckernförde Bucht and the Gulf of Mexico off Panama City, Florida (Principal Investigators: L.D.Wright and C.T. Friedrichs)

CBBL-SRP FY 1994 YEAR-END REPORT

L.D. Wright and C.T. Friedrichs

Virginia Institute of Marine Science
School of Marine Science
College of William and Mary
Gloucester Point, Virginia 23062

Summary of Work During the Period:

Most of the effort in FY 1994 was focused on: (1) completing analyses of field data collected in Eckernförde Bay and off Panama City; (2) interpreting the results of the field experiments; (3) developing mathematical models for explaining our observations; and (4) preparing journal articles and conference presentations reporting our results. In addition, effort near the end of the year was devoted to preparing field instrumentation for deployment off Key West in FY 1995.

Objectives:

The overall objective of this ongoing study is to elucidate the temporal and spatial variability of the processes that form, modify and preserve sedimentary strata in a variety of shelf settings. In the specific case of the VIMS component of the larger multi-institutional effort, we have been addressing questions related to; (1) hydrodynamic forcings (benthic physical oceanography); (2) fluid-bed coupling through the bottom boundary layer (e.g. bed stress measurement); (3) bed micromorphodynamics and roughness variations; (4) sediment resuspension; and (5) sediment flux divergence and bed level changes.

Results from Eckernförde Bay:

Analyses and interpretations of our results from the Eckernförde Bay experiments are reported in detail in the appended manuscript (Friedrichs and Wright, in press) which has been accepted for publication in *Continental Shelf Research*. A short version was also reported at the 1994 Ocean Sciences Meeting (Wright, 1994). The essence of the Eckernförde results is summarized below.

In spring 1993, an instrumented tetrapod was deployed in Eckernförde Bay, Baltic Sea, with the purpose of characterizing physical processes most relevant to sediment erosion, transport and deposition. Results suggest that sediment transport events in Eckernförde Bay are associated with resonant internal waves. Observed turbidity events were associated with marked along-bay current oscillations, and spectral analyses of these currents are highly suggestive of baroclinic resonance. Furthermore, the peak in the current spectra is remarkably close to the previously reported 26 to 28 hour Baltic-wide seiche. A one-dimensional, two-layer analytic model was developed to explain the generation of resonant

internal waves within Eckernförde Bay by periodic, barotropic flows across a sill near the mouth of the bay. The analytic solution accounts for velocities much larger than those otherwise predicted by barotropic processes or by progressive internal waves, and also explains an observed sign reversal in the correlation between barotropic forcing and the internal wave response. Despite this enhancement of near-bottom currents, estimates of shear velocity suggest that bottom stress never reached the critical magnitude necessary to locally resuspend sediment and was only rarely sufficient to prevent deposition of sediment that may have been suspended elsewhere. During turbidity events, observed suspended sediment concentration did not increase with proximity to the bottom, suggesting sediment advection rather than local resuspension. Bottom photographs support this inference. Although internal wave resonance may commonly produce velocities sufficient to advect fine sediment into Eckernförde Bay, maximum currents are constrained by the wave's phase velocity, which is only on the order of 30 cm s^{-1}.

Results from Panama City:

Field observations off Panama City were made at a depth of approximately 27 m over the period 13 August through 1 September 1993. A total of 151 bursts were obtained spanning 453 hours. The burst-averaged mean near-bottom currents never exceeded 14 cm s^{-1} and were usually less than 8 cm s^{-1}, generally reflecting the microtidal regime and weak wind stress of the observation period. Figure 1 shows the burst-mean current magnitudes and directions over the observation period and corresponding stick plots are shown in Figure 2. An abrupt change in direction near burst 88 was preceded by a sharp temperature drop and followed by a temperature increase of nearly 2° C (Figure 3). The long duration of the event suggests that it was related to mesoscale circulation and did not represent a response to direct meteorological or tidal forcing.

Throughout the record, bed stress remained well below the critical level necessary to suspend the relatively coarse sand composing the bed (median diameter ~ 0.65 mm). Accordingly, there was no correlation between near-bottom current speeds and suspended sediment concentrations (as measured by the optical backscatterance sensors). In fact, the highest concentrations tended to be associated with the weakest flows. Figure 4 shows time series of burst-averaged suspended sediment concentrations over the deployment duration. Two prominent and broad peaks are evident: the first, and lowest, coincided with the first cooling event on the 9th and 10th days of the record (bursts 76-88) and the second, larger turbidity increase corresponds with the second (and weaker) temperature drop following day 15 (burst 112). We infer that the observed episodes of high turbidity involved the advection of fines or marine "snow" within the cooler water masses.

Some Generic Analyses:

We have also been utilizing data from Eckernförde and Panama City along with data sets collected in other similar environments in an effort to gain a better understanding of some generic principles that control bottom boundary layer and sediment transport processes

in general. Specifically, we have been comparing results from Eckernförde with results recently obtained from the lower Chesapeake Bay (Wright *et al.*, in review). Both of these environments are characterized by low bed stresses and by biologically-mediated fine sediment transport and accumulation.

Data collected from the Louisiana inner shelf to the west of the active mouths of the Mississippi River at approximately the same time as the Panama City experiment has provided the opportunity for comparing boundary layer processes in the eastern and central Gulf of Mexico. Whereas the bed off Panama City is hydraulically very rough, the Louisiana inner shelf is quite smooth. In both cases, however, bed stresses tend to remain below the critical level required for sediment resuspension.

Instrument Preparation:

The electromagnetic current meters, optical backscatterance sensors, pressure sensors, acoustic altimeter, and thermistors that will be deployed off Key West in February 1995 were refurbished, adjusted and checked following their recovery from an extensive field experiment in the Middle Atlantic Bight that was completed in October 1994. These instruments are presently being calibrated and will be shipped to Key West in January 1995.

Publications and Presentations:

Friedrichs, C.T. and L.D. Wright, in press, Resonant internal waves and their role in transport and accumulation of fine sediment in Eckernförde Bay, Baltic Sea. *Continental Shelf Research* (manuscript attached).

Wright, L.D., 1994, Benthic transport phenomena in Eckernförde Bay (Baltic Sea). *Abstracts Volume, 1994 Ocean Sciences Meeting*, p. 180, Meeting held in San Diego, Feb 1994.

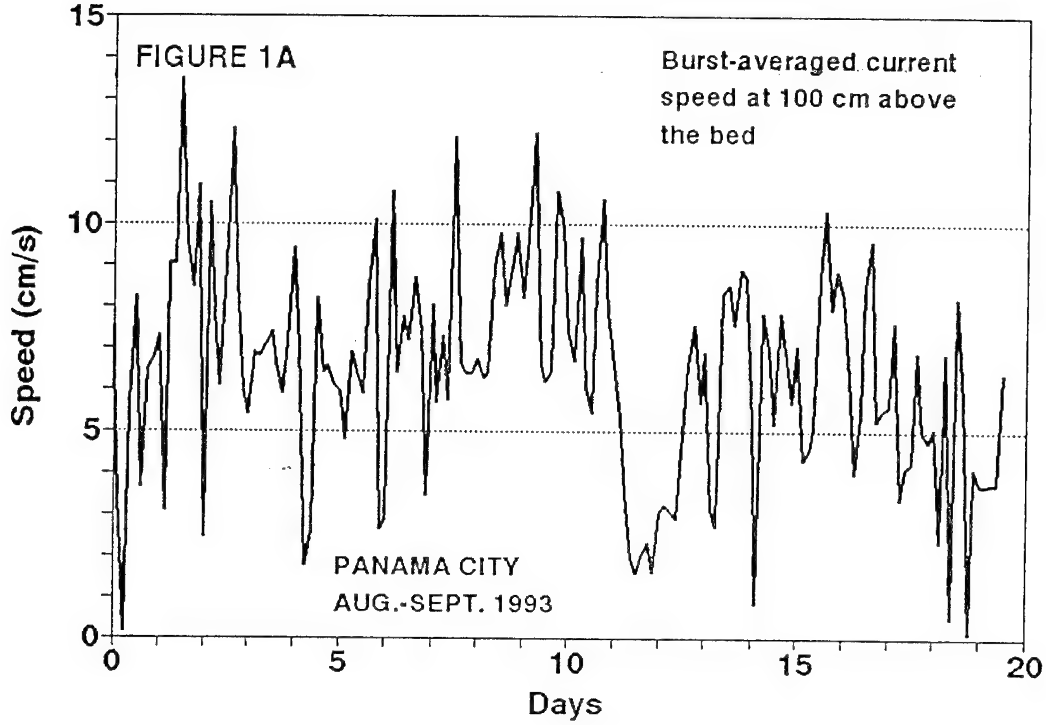


FIGURE 1A
Burst-averaged current speed at 100 cm above the bed
PANAMA CITY
AUG.-SEPT. 1993
Speed (cm/s)
Days
0
5
10
15
20

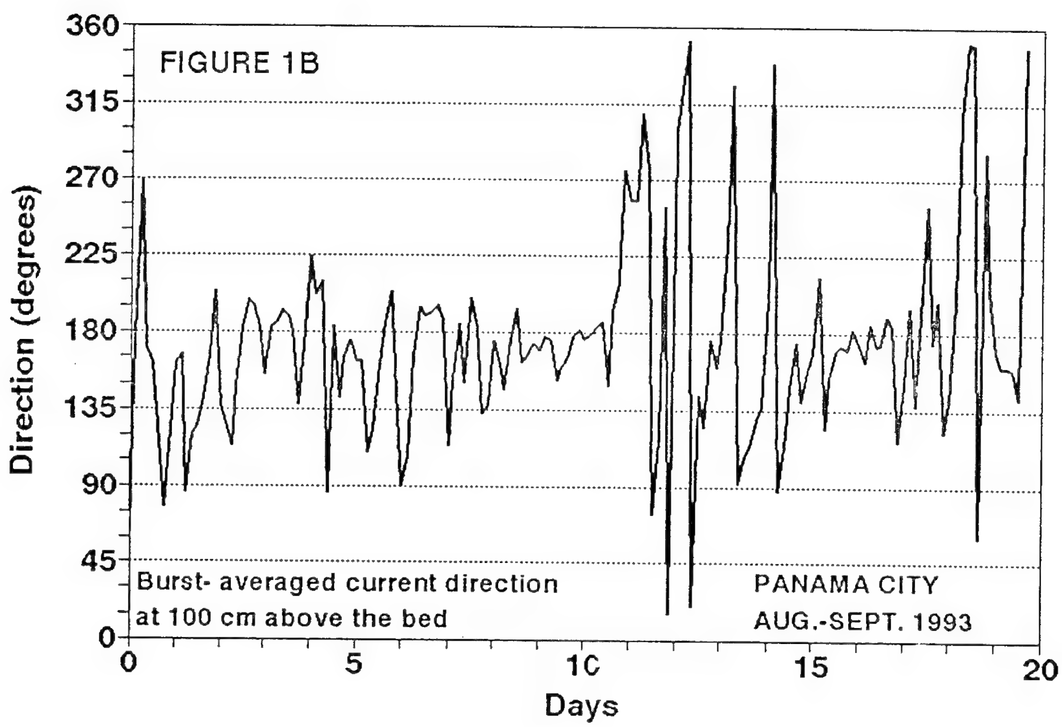


FIGURE 1B
Burst- averaged current direction at 100 cm above the bed
PANAMA CITY
AUG.-SEPT. 1993
Direction (degrees)
Days
0
45
90
135
180
225
270
315
360
5
10
15
20

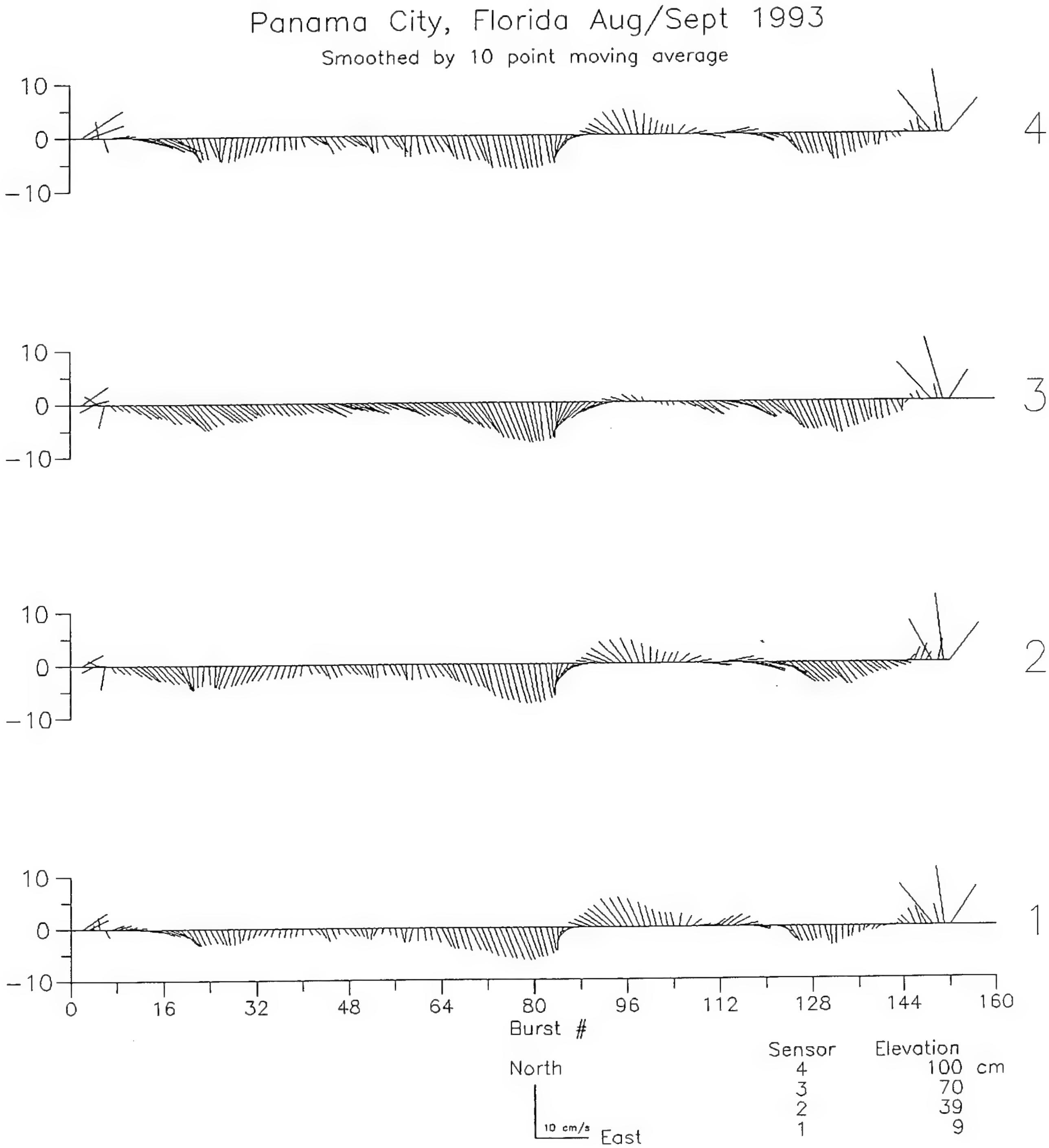


Figure 2 Stickplot of smoothed velocities at 4 elevations.

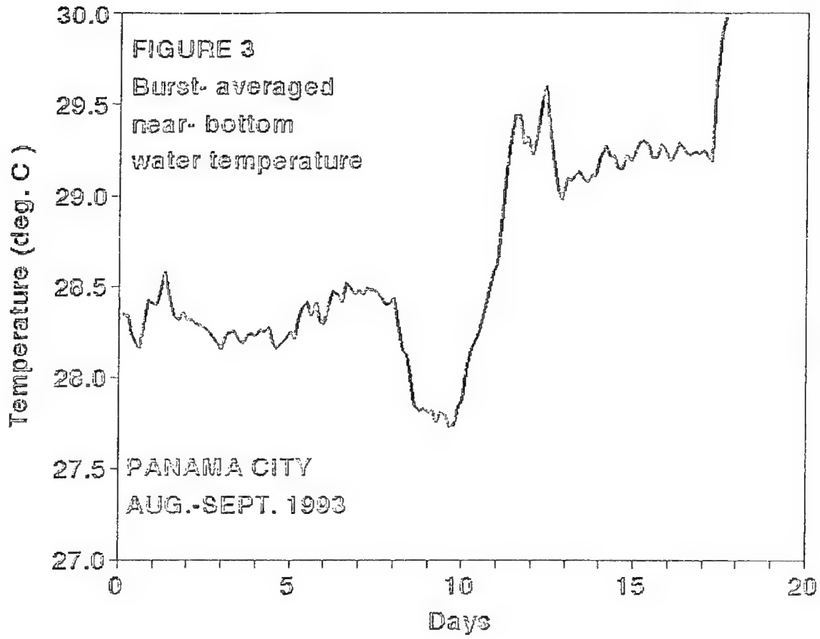


FIGURE 3
Burst- averaged
near- bottom
water temperature
PANAMA CITY
AUG.-SEPT. 1993
Temperature (deg. C)
Days
30.0
29.5
29.0
28.5
28.0
27.5
27.0
0
5
10
15
20

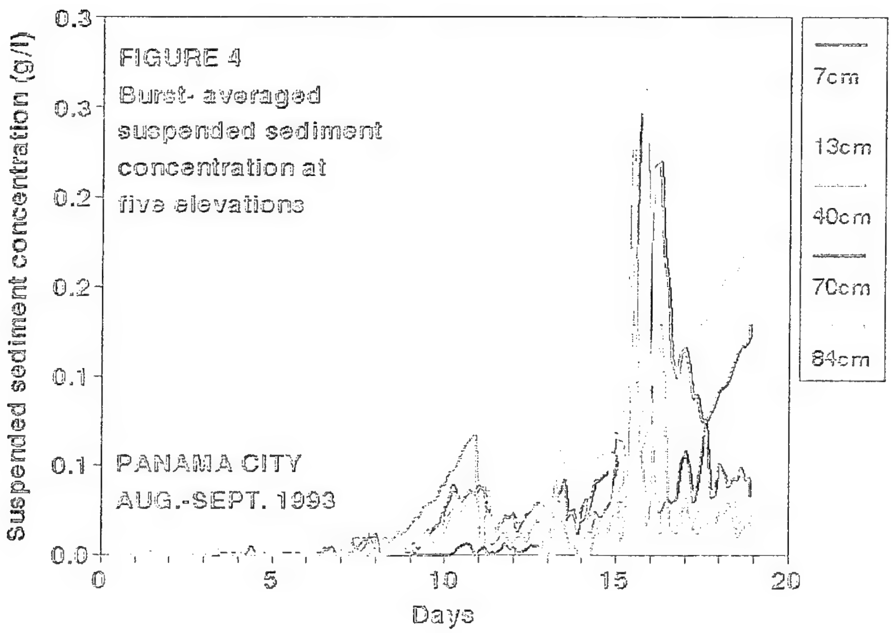


FIGURE 4
Burst- averaged
suspended sediment
concentration at
five elevations
PANAMA CITY
AUG.-SEPT. 1993
Suspended sediment concentration (g/l)
Days
7cm
13cm
40cm
70cm
84cm
0.3
0.3
0.2
0.2
0.1
0.1
0.0
0
5
10
15
20

2.22 Image Analysis of Sediment Texture: A Rapid Predictor of Physical and Acoustic Properties of Unconsolidated Marine Sediments and Processes Affecting Their Relationships (Principal Investigators: D.K. Young, R.J. Holyer and J.C. Sandidge)

CBBLSRP FY94 YEAR-END REPORT

David K. Young, Ronald J. Holyer and Juanita C. Sandidge

Naval Research Laboratory
Stennis Space Center
Mississippi 39529 USA

During FY94 image enhancements and texture analyses were performed on in situ cross-sectional photographs, box core x-radiographs, and electron photomicroscopy images of marine sediments. Images were digitized from original film products. Results of initial analyses were presented at the special session of the CBBLSRP at the February '94 AGU meeting (Holyer et al. 1994). A presentation of our image-based textural analysis approach was given at the "Gassy Mud" workshop at FWG on 11-12 July '94 (Young et al. 1994).

Fig. 1 shows a side-by-side comparison of imagery of sediment from the NRL tower site, Eckernfoerder Bucht, (from left to right): profile in situ photograph, profile x-radiograph, and electron photomicrograph. Our analyses of imagery of Eckernfoerder Bucht sediments from the May '93 experiment have shown greatest differences of sediment density structure at the microfabric scale of variability. Our analyses of imagery of marine sediments from other locations show that image-based textural structure dominates in these areas at larger scales. Image-based texture analytical results were compared with conventional analyses of measured sediment bulk properties. A manuscript (Holyer et al. 1995) on these results has been submitted for publication in a special publication of GeoMarine Letters. A summary of conclusions arising from this work follows.

<u>Summary of Image Processing Work:</u> Image analysis of x-radiographs has shown correlation lengths for the Eckernfoerde Bay sediments sample to be longer by an order of magnitude than correlation lengths computed for the Arafura Sea sample. Horizontal and vertical correlation lengths are nearly equal for the Arafura Sea data, but highly asymmetrical (longer correlation lengths horizontally than vertically) for Eckernfoerde Bay. These observations are consistent with and serve to quantify other observations at these sites. Sediments from the NRL site in Eckernfoerde Bay are high porosity clayey silt deposits characterized by little down-core variability in bulk sedimentary properties. Relatively high sedimentation rates and bioturbation activities limited to the upper 1 cm of sediment have permitted physical laminations, such as storm deposits, to be preserved intact (Richardson, 1994). These laminations, most clearly seen in the binary version (Fig. 2) of a typical x-radiograph (Fig. 3) are, in large part, responsible for density features that result in the observed anisotropy in correlation length. These thin laminae are destroyed by most conventional measurements and, hence, are not quantified by down core bulk properties, such as average grain density and porosity (Fischer and Farno, 1993).

By contrast, sediments from the Arafura Sea site are well-mixed sand and gravel-sized particles (averaging 55% of sample weight) embedded in a silty clay matrix (Briggs, et al., 1989). The coarse particles are comprised of a shell-hash mixture of mollusc shells, shell fragments and carbonate rocks (Briggs, 1994). The random placement of particles in this well-mixed sediment explains the isotropic correlation lengths observed in the binary version (Fig. 4) of a typical x-radiograph (Fig. 5). Jackson and Briggs (1992) note that larger particles are responsible for the observed frequency independent acoustic response in which sediment volume scattering was dominant and no backscattering anisotropy was exhibited.

Image-based correlation lengths are in general agreement with those calculated from a down-core series of porosity and compressional sound velocity measurements for the Arafura Sea sample (Fig. 6). However, for the Eckernfoerde Bay sample the conventional and image-based correlation length results were very different (Fig. 7). We conclude that this result supports the previous interpretation that in Eckernfoerde Bay, laminae yielding the large horizontal correlations lengths are not represented in the conventional down-core measurements of bulk sediment properties.

Particle size distributions inferred from image segmentation followed by run length calculations agree favorably with particle size distributions measured by conventional means for Arafura Sea sediment (Fig. 8). No comparable data were available for run length analyses of Eckernfoerde Bay sediments (Fig. 9). Run lengths for particles and voids did not exhibit strong anisotropy. On particle size scales both sediment samples studied fail to show directionality. The anisotropy observed in correlation length occurs at larger scales formed by laminae of particles, not by particle geometry or orientation.

Image-based texture analysis of sediment x-radiographs has significant advantages over conventional methods. Among those advantages are nonintrusiveness,characterization of voids, quantification of anisotropy, and continuous high-density sampling. Conventional sediment textural analysis methods have advantages in that they have been used over many years and are represented by a rich database useful for modeling and predictive purposes. Adding image-based techniques to the sedimentologists' tool box should prove to be beneficial where conventional methods prove to be too time-consumptive, costly, or impractical. Image-based methods are particularly promising when conventional methods do not provide adequate parameterization for predictive purposes. An example is the sediment (acoustic) volume scattering strength which is presently used in geoacoustic models as a free parameter (Jackson and Briggs, 1992).

June-July'94 Experiment: During the June-July '94 experiment, one project investigator (DKY) participated in various field operations, including SCUBA diving and chamber "dives", in cooperation with other CBBLSRP scientists. We used the NRL-SSC diver-operated sediment profile camera to document organism-sediment relations and to gain in situ information about sediment texture by obtaining high resolution photographs of the sediment-water interface.

X-radiographs of box-core sediments were obtained (cooperatively with Kevin Briggs) from a variety of benthic environments in Eckernfoerder Bucht where measurements of sediment properties have been collected by other CBBLSRP scientists. Sites sampled include: the APL Tower site (BC#619), the NRL Tower site (BC# 634, 680), and a series along the "Schock Line" (BC# 651, 652, 658, 662, 663). All x-radiograph samples were photographed to document down-core changes of color and texture. Some of these x-radiographs allowed subsampling from specified locations within the cores (via one side being removable) for electron microscopy of microfabric (cooperatively with Dennis Lavoie) and for grain size and index property analyses (cooperatively with Dawn Lavoie). Our analyses of imagery of these samples will permit us to compare differences from known sample locations and depths with image-based measures of texture from the microfabric scale to the macrostructural scale of variability.

Future Plans: We are in the process of analyzing x-radiographs of logged deep cores from Eckernfoerder Bucht (cooperatively with Bill Bryant and Niall Slowey). Image-based textural parameters will be compared with measured sediment density and other bulk property values. We plan to analyze imagery of sediments over a wide range of size scales and different sedimentary environments to obtain statistical estimates of measured sediment properties and geoacoustic parameters. We will extend our approach to include fractal geometry, which may allow us to better identify, quantify and scale processes responsible for resultant sediment textural structure.

PRESENTATIONS

Holyer, R. J., D. K. Young, J. R. Chase, and K. D. Briggs (1994) Sediment density structure inferred by textural analysis of cross-sectional x-radiographs and electron microscopy images. EOS, Transactions, American Geophysical Union, 75 (3):202.

Young, D. K., R. J. Holyer, and J. C. Sandidge (1994) Texture of sediments from Eckernfoerder Bucht: An image analysis approach. Gassy Mud Workshop, FAG, 11-12 July 1994.

PUBLICATIONS

Holyer, R. J., D. K. Young, J. C. Sandidge, and K. B. Briggs (1995) Sediment density structure inferred by textural analysis of cross-sectional x-radiographs. GeoMarine Letters, submitted.

REFERENCES

Briggs, K. B. (1994) High-frequency acoustic scattering from sediment interface roughness and volume inhomogeneities. PhD Dissertation, U. Miami, Coral Gables, FL, 143 pp.

Briggs K. B, P. Fleischer, W. H. Jahn, R. I. Ray, W. B. Sawyer, and M. D. Richardson (1989) Investigation of high-frequency acoustic backscattering model parameters: environmental data from the Arafura Sea. Naval Ocean Research and Development Activity Report 197, February, 94 pp.

Fischer, K. M. and C. L. Farno (1993) Sediment geochemical processes: field participation at Eckernfoerde Site (Coastal Benthic Boundary Layer Special Research Project). Naval Research Laboratory, Stennis Space Center, MS NRL/MR/7432--93-7076.

Jackson, D. R. and K. B. Briggs (1992) High-frequency bottom backscattering: Roughness versus sediment volume scattering. Journal of the Acoustic Society of America, 92(2): 962-977.

Richardson, M. D. (1994) Coastal benthic boundary layer research program: a review of the first year, vol. I,. Naval Research Laboratory, Stennis Space Center, MS, NRL/MR/7431--94-7099.

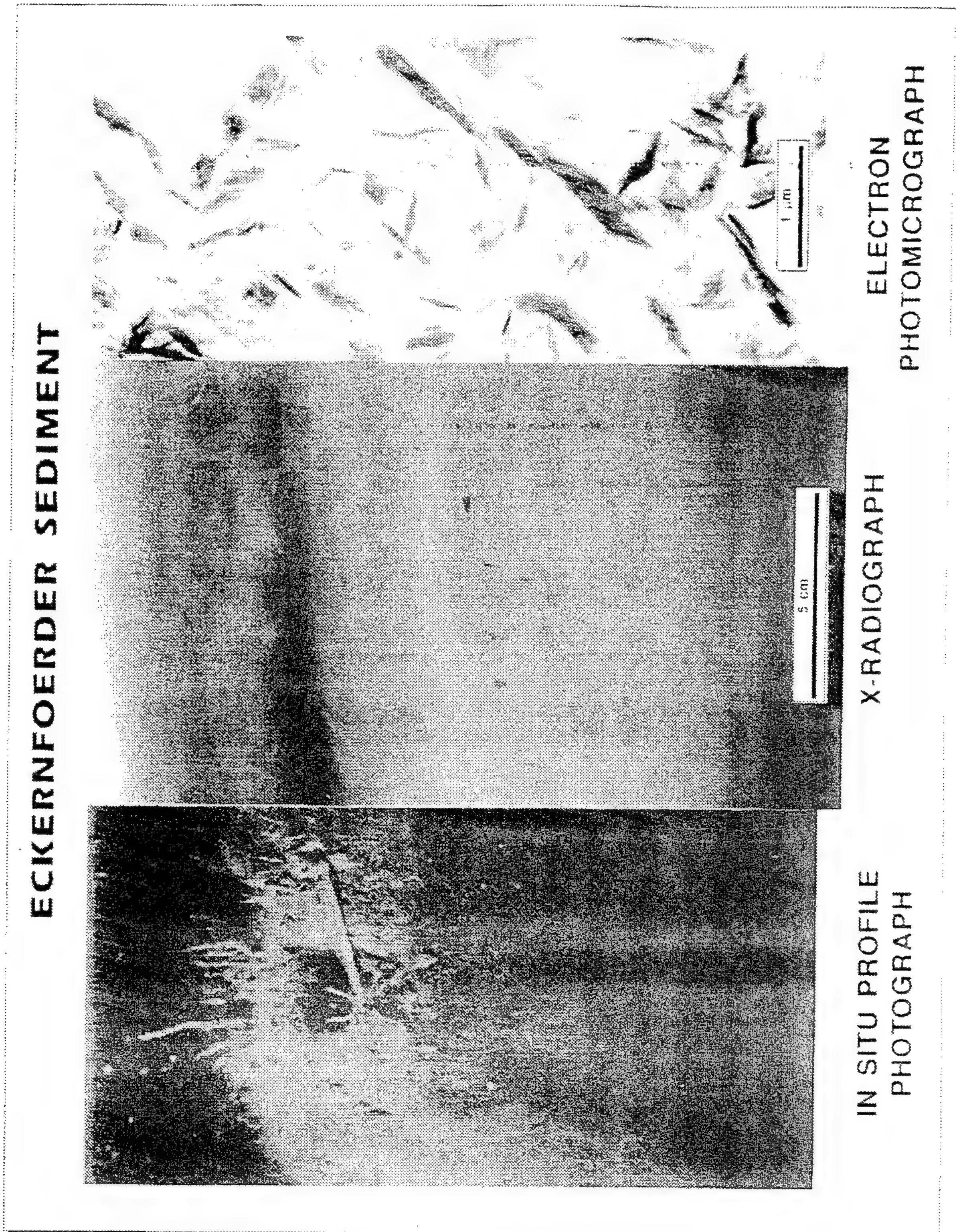


Figure 1. Imagery of sediment from Eckernfoerder Bucht: profile in situ photograph (left), profile x-radiograph (middle), and electron photomicrograph (right).

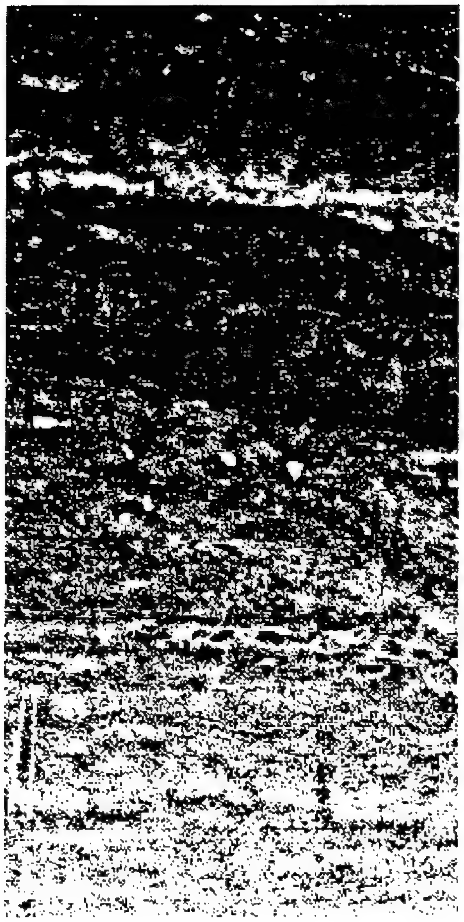


Figure 2. Binary version of Fig. 3 image, generated by Wallis Filtering and thresholding.

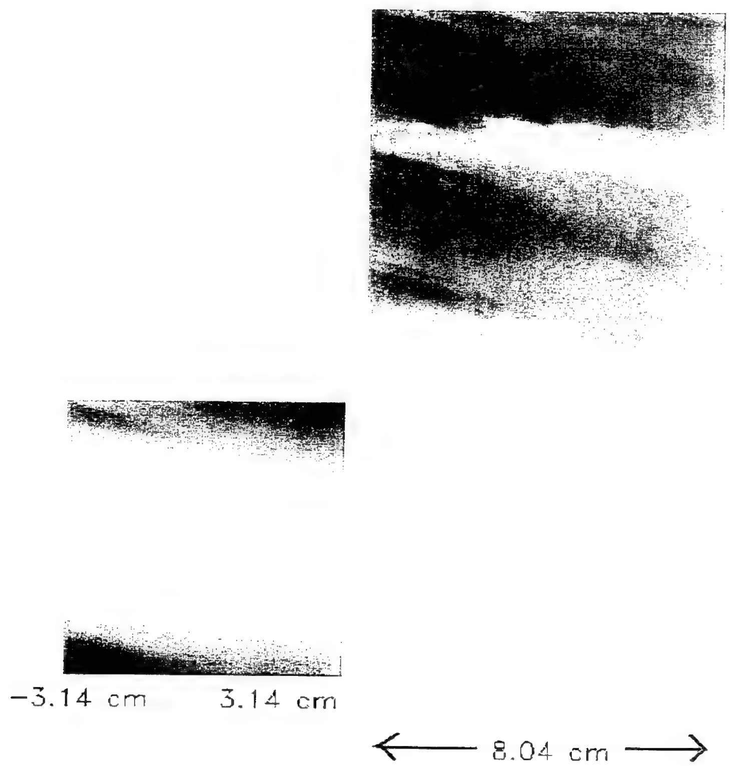


Figure 3. Subsection of a typical Eckernfoerde Bay (Germany) x-radiograph (right) and its autocorrelation function (left).

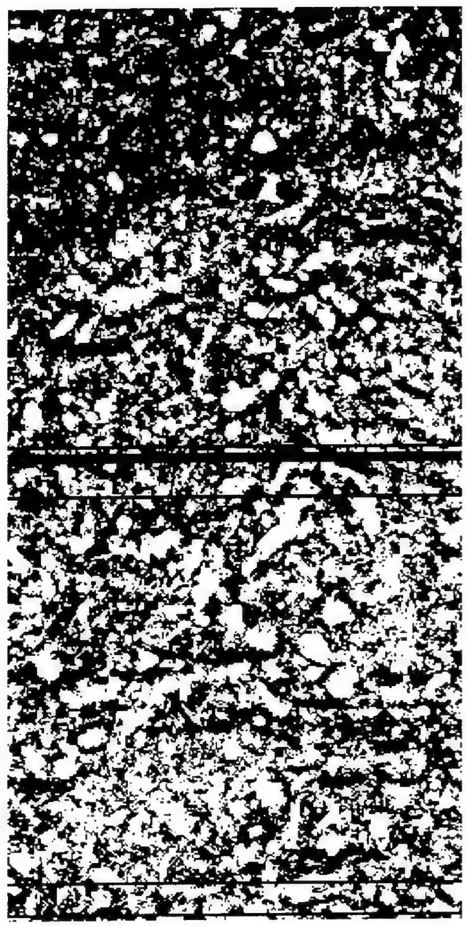


Figure 4. Binary version of Fig. 5, binary form generated by Wallis filtering and thresholding.

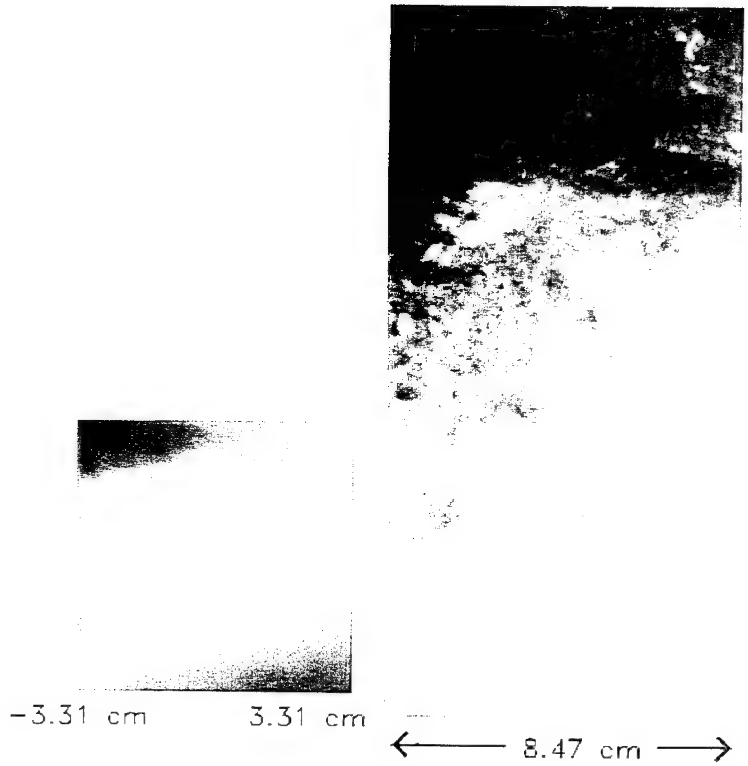


Figure 5. Subsection of a typical Arafura Sea (Australia) x-radiograph (right) and its autocorrelation function (left).

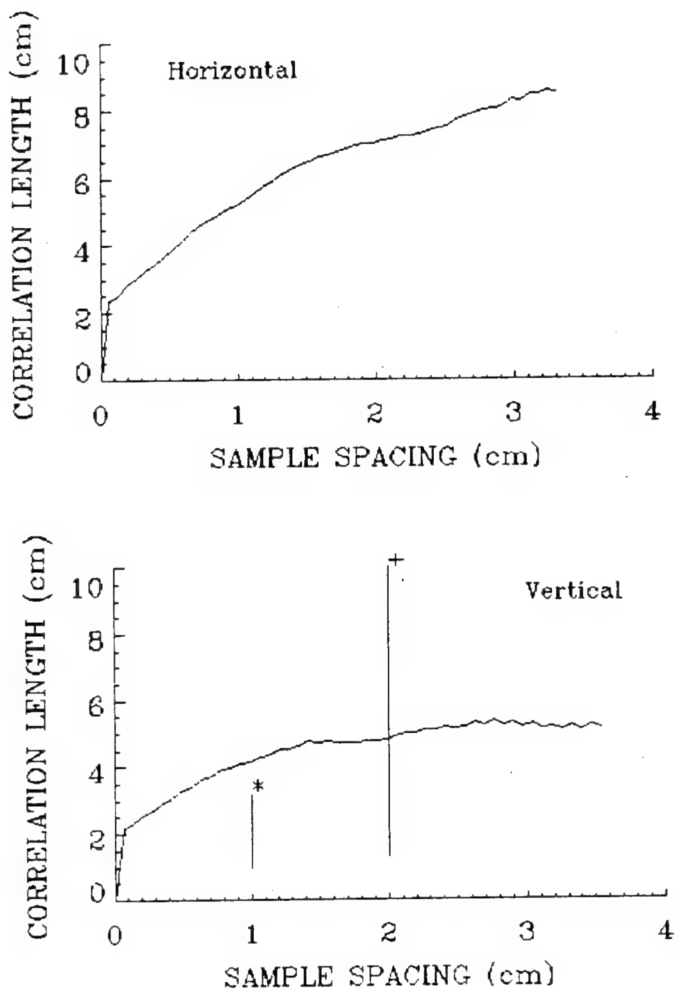


Figure 6. Horizontal and vertical correlation lengths calculated using the autocorrelation function shown in Fig. 5. Correlation lengths are calculated for all autocorrelation lags (sample spacings) from 0 to 3.31 cm. Vertical lines in plots indicate the range of correlation length values for Arafura Sea sediments derived by conventional [down-core porosity (+) and compressional sound velocity (*)] methods (Briggs et al., 1994).

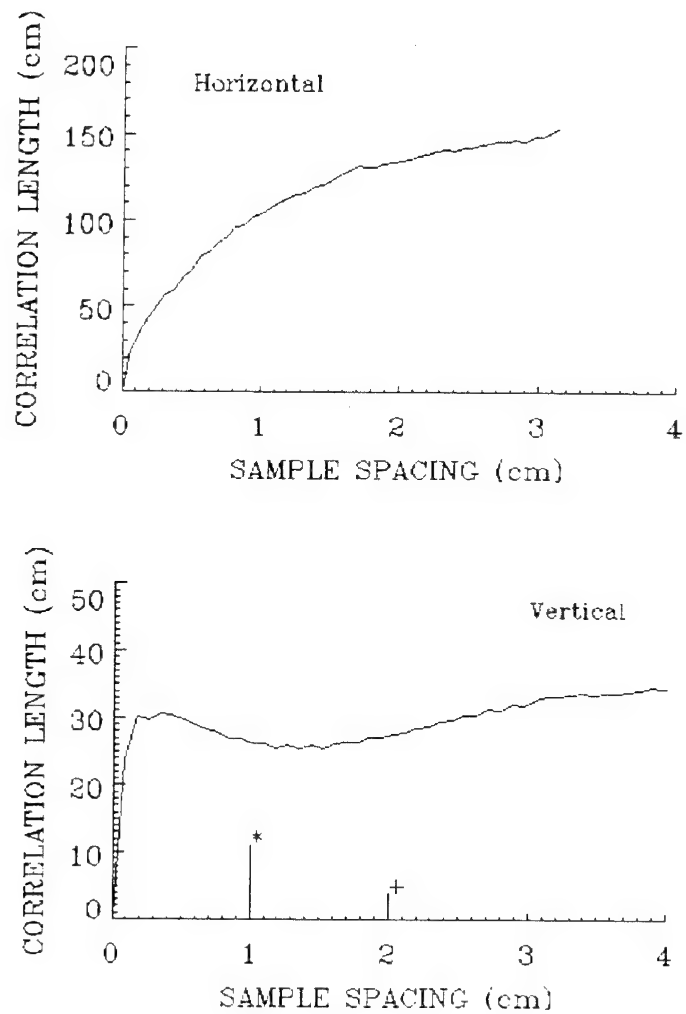


Figure 7. Horizontal and vertical correlation lengths calculated from the autocorrelation function also shown in Fig. 3. Correlation lengths are calculated for all autocorrelation lags (sample spacings) from 0 to 3.14 cm. Vertical lines in plots indicate the range of correlation length values for Eckernfoerde Bay sediments derived by conventional [down-core porosity (+) and compressional sound velocity (*)] methods (Briggs et al., 1994).

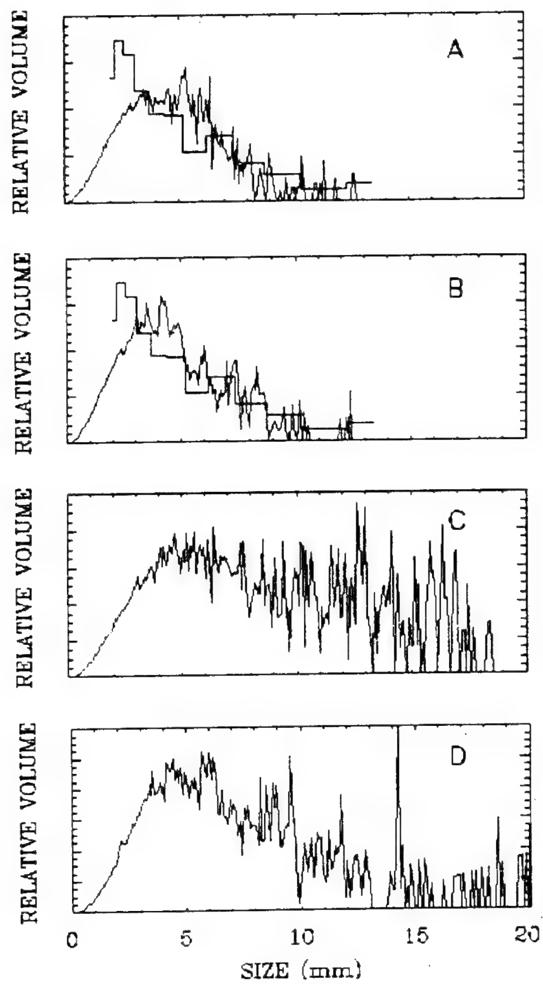


Figure 8. Volumetric size distributions of particles and voids estimated from white and black run lengths in Fig. 4. (A) Horizontal volume compensated run length distribution for particles (continuous curve). Average horizontal particle run length is 0.89 mm. Step-wise curve is conventional volumetric size distribution from Briggs et al. (1994). (B) Same as (A) but for the vertical direction. Average vertical particle run length is 0.91 mm. (C) Horizontal volume compensated run length distribution for voids. Average horizontal void run length is 1.28 mm. (D) Same as (C) but for the vertical direction. Average void run length is 1.37mm.

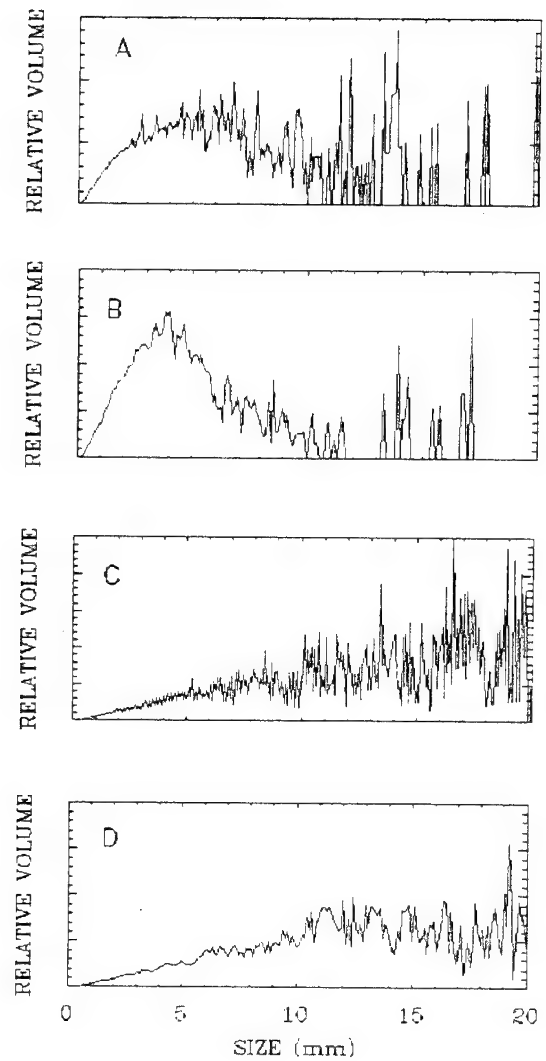


Figure 9. Volumetric size distributions of particles and voids estimated from white and black run lengths in Fig. 2. (A) Horizontal volume compensated run length distribution for particles. Average horizontal particle run length is 0.47 mm. (B) Same as (A) but for the vertical direction. Average vertical particle run length is 0.64 mm. (C) Horizontal volume compensated run length distribution for voids. Average horizontal void run length is 0.81 mm. (D) Same as (C) but for the vertical direction. Average vertical void run length is 1.15 mm.

2.23 Variability in Bottom Backscattering Data Due to Sea Water Temporal Temperature Fluctuations (Principal Investigator: L. Zhang)

VARIABILITY IN BOTTOM BACKSCATTERING DATA DUE TO SEA WATER TEMPORAL TEMPERATURE FLUCTUATIONS

(Principal Investigator: Li Zhang, University of Southern Mississippi)

CBBLSRP FY94 YEAR-END REPORT

by

Li Zhang
Center for Marine Science
University of Southern Mississippi
Stennis Space Center, MS 39529

INTRODUCTION

Usually bottom acoustic backscattering measurements are conducted through ship-mounted systems. The floating measurement systems are responsible for the fluctuations in measurement data and the average values are used as final results. In both CBBLSRP acoustic backscattering sites, the high frequency backscattering measurement system was composed of a acoustic transducer which was fixed on the top of a tower standing on the seafloor. Fluctuations were also found in the measured data for such a fixed-geometry measurements. A hypothesis was presented in last year's report that temperature fluctuations associated with turbulence in seawater can account for the acoustic variability[1]. This report discusses the relationship between acoustic variability and sea water temporal temperature and sound speed fluctuations. The comparisons between measured data and the model were presented in Acoustical Society of America's Austin meeting[2].

FLUCTUATIONS IN BACKSCATTERING DATA

An expression for the backscattering sound pressure from sea bottom was presented in last year's report which can be written as[1,2]

$$p = \iint_{S_0} Q \sin(\omega t - 2kr)\, dS_0 \qquad (1)$$

where the quantity Q may be regarded as source strength of scattering sources distributed on the seafloor, defined as:

$$Q = \frac{-kA}{(4\pi r)^2}\,(1+R)\,(1+R_0)\,\cos\theta_t\,(\beta-\beta_0) \tag{2}$$

where A is a constant related to source strength, r is the distance between the source and the insonified area on the seafloor, Θ_t is the refraction angle, β_0 and β are average and local specific acoustic admittance, and **R** and $\mathbf{R}_0$ are local and average reflection coefficient, respectively. Suppose the scatterers are discrete points distributed on the boundary then the scattering wave becomes

$$p = \sum_{j=1}^{N} Q_j \sin[\omega(t-\frac{2r_j}{c_0})]\,\Delta s_j \tag{3}$$

where Q_j is similar to Equation (2) for the *j*th scatterer, Δs_j is *j*th scatterer's area and r_j is its distance to the sound source. The scattered sound field depends on the total number of scatterers N within the insonified area S_0, and more important, on the relative phase differences among those scatterers. The insonified area S_0 is determined by beam-pattern of the sound source and pulse length for pulsed continuous-wave signals.

The properties in seawater will fluctuate as a result of the dynamic process like turbulence in water. Since the perturbations of the density and the sound speed in seawater is usually very small, compared with the fluctuations in the sediment, the volume reverberation in the seawater can be neglected here. But the relative phases will be different if the sound speed in seawater changes. Considering the presence of inhomogeneity in seawater, both density and sound speed are spatial and temporal functions now. Assuming the fluctuations in density and in sound speed is small, the amplitudes of the scattering waves, indicated by Q in Equation (2) or Q_j in Equation (3), are almost keep unchanged. However, the phase term is very sensitive to the fluctuations of the sound speed in seawater for high-frequency signals.

As the sound speed in seawater changes from its average value c_0 to c, $c = c_0 + \delta c$, due to existing of the turbulence, then the phase term will differentiate from its original value. A critical sound speed fluctuation was defined as the phase change reaches 90°

$$\delta c_c = \frac{c_0^2}{8fr} \tag{4}$$

If δc is greater than critical sound speed fluctuation, the variability in acoustic data becomes obvious. For the case of Panama City site measurement, 40 kHz of frequency and 14 m of the distance b (30° grazing angle), δc_c value is 0.5 m/s, corresponding to seawater temperature fluctuation in the order of 0.1 °C[3]. It seems not to be an unreasonable magnitude. Similar order of sound speed fluctuations near the sea surface was reported in Reference [4].

When sound speed in seawater is no longer a constant, the scattering field should be written as

$$p = \sum_{j=1}^{N} A_j \sin[\omega(t - \frac{2r_j}{c_j})] \tag{5}$$

where $A_j = Q_j \Delta s_j$, the amplitude of the *j*th scatterer, and c_j is the sound speed associated with *j*th scatterer, which may be different from the others.

When $\delta c \ll c_0$, the Equation (5) becomes

$$p = \sum_{j=1}^{N} A_j \sin(\omega t - \frac{2\omega r_j}{c_0} + \frac{2\omega r_j}{c_0} \frac{\delta c}{c_0}) \tag{6}$$

According to the definition of the sound intensity,

$$I = \frac{1}{\rho c} \frac{1}{T} \int_0^T p^2 \, dt \tag{7}$$

the backscattering sound intensity is then

$$I = \frac{1}{2\rho c_0} \sum_{i=1}^{N} \sum_{j=1}^{N} A_i A_j \cos[2\omega(\frac{r_i}{c_i} - \frac{r_j}{c_j})] \tag{8}$$

The simplest case is that the sound speed is a constant c_0, then sound intensity is

$$I_0 = \frac{1}{2\rho c_0} \sum_{i=1}^{N} \sum_{j=1}^{N} A_{ij} \cos \Phi_{ij} \tag{9}$$

where $A_{ij} = A_i A_j$, and $\Phi_{ij} = 2\omega(r_i - r_j) / c_0$, the phase difference between the *i*th and the *j*th scatterer.

Now assuming for every scatterers the sound speed is same, but it is a function of time. That means we only consider the temporal fluctuations of the sound speed. Suppose sound speed satisfies uniform distribution within a range from $(c_0 - \Delta)$ to $(c_0 + \Delta)$, then the mean value of sound intensity is

$$I = \frac{1}{2\rho c_0} \sum_{i=1}^{N} \sum_{j=1}^{N} A_{ij} \cos\Phi_{ij} \; \frac{\sin\Phi_{ij}\varepsilon}{\Phi_{ij}\varepsilon} \tag{10}$$

where $\varepsilon = \Delta / c_0$, relative variation of sound speed. When the fluctuation in sound speed is small, its mean and standard deviation is

$$I = I_0 \tag{11}$$

$$\sigma_I^2 = \frac{1}{3} \left[\frac{\varepsilon}{2\rho c_0} \sum_{i=1}^{N} \sum_{j=1}^{N} A_{ij} \, \Phi_{ij} \, \sin\Phi_{ij} \right]^2 \tag{12}$$

The condition for these two equations are approximately $\Phi_{ij}\ \varepsilon < 1$. In high frequency acoustic measurements, the insonified area is usually determined by pulse length τ, and so does the distance difference $(r_i - r_j)$. Therefore, Equation (11) requires that

$$\tau < \frac{c_0}{\omega\Delta} \tag{13}$$

Let Δ be 0.5 m/s, for 100 kHz frequency, pulse length τ should be less than 5 ms, in order to let average sound intensity close to its real value.

Considering Bragg scattering, every two point scatterers are in phase for a specific frequency at some certain locations. Set $\Phi_{ij} = n \cdot 2\pi$ ($n = 0, \pm 1, \pm 2, \pm 3, \ldots$) in Equation (12), it is found that there is no fluctuations in sound intensity. It is an interesting result because the surface roughness scattering is more like to show Bragg scattering feature. If the scattering is mainly due to surface roughness, acoustic data show less fluctuations. In contrast, if discrete point scatterers are more important, bigger variability will be observed in backscattering measurements.

Obviously σ_I vanishes if there is only single scatterer within the insonified area. It can also be expected than σ_I tends to zero as number of scatterers is very large and the relative phases are randomly distributed. But the actual fluctuation is more complex. The following discussions provide an estimation of the acoustic variability in the sense of scaling. First in Equation (12), an average Φ_0 value will be used to substitute Φ_{ij}. Next, approximately,

$$\sum_{i=1}^{N} \sum_{j=1}^{N} A_{ij} \sin\Phi_{ij} \approx \sum_{i=1}^{N} \sum_{j=1}^{N} A_{ij} \cos\Phi_{ij} \tag{14}$$

for a random distribution of fairly large number of scatterers. Then Equation (12) becomes

$$\frac{\sigma_I}{I_0} = \Phi_0 \frac{\sigma_c}{c_0} = \frac{4\pi f\ \Delta r}{c_0}\ \frac{\sigma_c}{c_0} \tag{15}$$

here Δ has been changed into the standard deviation of sound speed, $\sigma_c = \Delta/3$, and Δr is the average value of distance difference. Using $\Delta r = \frac{1}{2}\ (\frac{1}{2} c\tau)$, finally we obtain

$$\frac{\sigma_I}{I_0} = \pi\ \tau\ f\ \frac{\sigma_c}{c_0} \tag{16}$$

It states that higher frequency and/or longer pulse length, more fluctuations in acoustic data. Numerical simulations suggest that higher fluctuations if the sound frequency becomes higher, but the measured data do not have such apparent trend[2].

CONCLUSIONS

Even for fixed-geometry measurement systems, the fluctuations can still be observed in high frequency backscattering experiments. The fluctuations in seawater can account for the fluctuations. Theoretical analysis suggest that higher acoustic variability occurs at higher frequency and/or higher sound speed fluctuations. For high frequency acoustic backscattering measurements, pulse length τ should not be too long. Longer pulse length not only decreases the spatial resolution but also leads to higher fluctuations in acoustic data, and the average value may not be used to calculate bottom backscattering strength. The calculated curves are based on discrete point scatterers. It is expected that scattering from surface roughness may show a different response to seawater turbulence.

There are some possible applications to study the backscattering fluctuations: prediction the order of the seawater turbulence; distinction of different backscattering mechanisms, estimating the number of scatterers. All of these remain in future study.

REFERENCES

[1] Zhang, L., "The relationship between high-frequency acoustic scattering and seafloor structure", section 3.24 in "Coastal Benthic Boundary Layer Special Research Program: A review of the first year, Volume I", edited by M. D. Richardson, Naval Research Laboratory, Stennis Space Center, Mississippi, April 6, 1994.

[2] Zhang, L., Goodman, R.R., and Stanic, S., "Acoustic pulse to pulse variability due to sea water temporal temperature fluctuations", *J. Acoust. Soc. Am.*, Vol. 96, No. 5, Pt. 2, p. 3286.

[3] Clay, C.S., and Medwin, H., *Acoustical Oceanography: Principles and Applications*, John Wiley & Sons, New York, 1977.

[4] Seymour, Harry A., Jr., "Statistical relations between salinity, temperature and speed of sound in the upper ocean", Master's Thesis, Naval Postgraduate School, Monterey, California, 1977.

3.0 LIST OF CBBLSRP RELATED PUBLICATIONS

JOURNAL ARTICLES

Abegg, F. 1994. Methoden zur Unterschung methanhaltiger mariner Weichsedimente. Meyniana 46, 1-9, Kiel.

Bautista, E., and R.D. Stoll. In press. Remote determination of in situ sediment parameters using love waves. J. Acous. Soc. Am.

Bennett, R.H., M.H. Hulbert, M. Meyer, D. Lavoie, K.B. Briggs, D. Lavoie, R.J. Baerwald and W.-A. Chiou. Submitted. Fundamental response of pore water pressure to microfabric and permeability characteristics: Eckernfoerde Bay. Geo-Marine Letters.

Bentley, S.J., C.A. Nittrouer and C.K. Sommerfield. Submitted. Development of sedimentary strata in Eckernfoerde Bay, southwestern Baltic Sea. Geo-Marine Letters.

Brandes, H.G, A.J. Silva, A. Ag, and G.E. Veyera. Submitted. Consolidation and permeability characteristics of surficial high porosity sediments in Eckernförde Bay. Geo-Marine Letters.

Briggs, K.B., and M.D. Richardson. Submitted. Variability of in situ shear strength of gassy sediments. Geo-Marine Letters.

Bryant, W.R., T.H. Orsi, N.C Slowey and K.S. Submitted. Processes of macroscale volume inhomogeneity in the benthic boundary layer in Eckernförde Bay, Baltic Sea. Geo-Marine Letters.

Chotiros, N.P. 1995. Biot model of sound propagation in water saturated sand. J. Acoust. Soc. Am., 97(1):199.

D'Andrea, A.F., G.R. Lopez and N.I. Craig A.F. Submitted. Benthic macrofauna and bioturbation in Eckernfoerde Bay, Southwestern Baltic Sea. Geo-Marine Letters.

Davis, A., D. Huws and R. Haynes. Submitted. Geophysical ground-truthing experiments in Eckernfoerde Bay. Geo-Marine Letters.

Davis, K.S., N.C. Slowey, I.H. Stender, H. Fiedler, W.R. Bryant and G. Fiechner. Submitted. Correlating acoustic backscatter with sediment textural properties. Northeastern Gulf of Mexico. Geo-Marine Letters.

Faas, R.W. Submitted. Resuspension, 'fluid mud' formation, and fine-sediment behavior in Eckernfoerde Bay, Western Baltic Sea. Geo-Marine Letters.

Fleischer, P., W.B. Sawyer, H. Fiedler and I.H. Stender. Submitted. Spatial and temporal variability of coarse-sand anomaly on a sandy inner shelf, Northeastern Gulf of Mexico. Geo-Marine Letters.

Friedrichs, C.T., and L.D. Wright. In press. Resonant internal waves and their role in transport and accumulation of fine sediment in Eckernfoerde Bay, Baltic Sea. Cont. Shelf Res..

Fu, S.S., R.H. Wilkens and L.N. Frazer. Submitted. In situ velocity profiles in gassy sediments: Eckernfoerde Bay. Geo-Marine Letters.

Holyer, R.J., D.K. Young, J.R. Chase and K.B. Briggs. Submitted. Sediment density structure derived from textural analysis of cross-sectional x-radiographs. Geo-Marine Letters.

Jackson, D.R., K.L. Williams and K.B. Briggs. Submitted. High-frequency acoustic observations of benthic spatial and temporal variability. Geo-Marine Letters.

Jackson, P.D., and K.B. Briggs. Submitted. Evaluation of sediment heterogeneity using micro-resistivity imaging and x-radiography. Geo-Marine Letters.

Jin, G., and D. Tang. Submitted. Uncertainties of differential phase estimation associated with interferometric sonars. IEEE Journal of Ocean Engineering.

Lavoie, D., M. Richardson, K.B.Briggs, E. Bautista, R. Stoll and A. Pittenger. Submitted. Panama City sands: geotechnical and geoacoustic variability. Geo-Marine Letters.

Lavoie, D., D. Lavoie. A. Pittenger and R. Bennett. Submitted. Bulk sediment properties interpreted in light of qualitative and quantitative microfabric analysis. Geo-Marine Letters.

Lavoie, D.L., S.R. Griffin and F.B. Groscz. Submitted. DIAS: A novel technique for measuring in situ shear modulus. Geo-Marine Letters.

Lyons, A., M. Duncan, J. Hawkins and A. Anderson. Submitted. Predictions of the acoustic response of free methane bubbles in muddy sediments. Geo-Marine Letters.

Orsi, T.H., A.L. Anderson and K. Fischer. Submitted. Relationships between sediment macrostructure and physical property variability. Geo-Marine Letters.

Orsi, T.H., A.L.Anderson and A.P. Lyons. In press. X-Ray tomographic analysis of sediment macrostructure and physical property variability in Eckernförde Bay sediments, Western Baltic Sea. Geo-Marine Letters.

Orsi, T.H., F. Werner, D. Milkert, A.L. Anderson and W.R. Bryant. Submitted. Environmental overview of Eckerförde Bay, Northern Germany. Geo-Marine Letters.

Richardson, M.D., and S. G. Tooma. 1993. Environmental requirements to support mcm operations in shallow water, Journal of Underwater Acoustics (USN) 43(3):977-991

Richardson, M.D. and K.B. Briggs. 1993. On the use of acoustic impedance values to Determine sediment properties, pps 15-25. In: N.G. Pace and D.N. Langhorne(eds.) Acoustic Classification and Mapping of the Seabed, Institute of Acoustics, University of Bath.

Richardson, M.D. 1994. Investigating the coastal benthic boundary layer. EOS, Transactions, AGU, 75(17) 201-206.

Richardson, M.D., and K.B. Briggs. Submitted. In-situ and laboratory geoacoustic measurements in soft mud and hard-packed sand sediments. Geo-Marine Letters.

Schock, S.G. and L.R. LeBlanc. Submitted. Sediment classification using normal incidence, FM reflection data. Geo-Marine Letters.

Silva, A J., H.G. Brandes and G.E. Veyera. Submitted. Geotechnical characterization of surficial high porosity sediments in Eckernförde Bay, Baltic Sea. Geo-Marine Letters.

Slowey, N., W.R. Bryant and D.N. Lambert. Submitted. Comparison of high-resolution seismic profiles and the physical and geoacoustic properties of sediments in Eckernförde Bay, Baltic Sea. Geo-Marine Letters.

Slowey, N.C. and W.R. Bryant. Submitted. Effects of gas and core handling on measurements of compressional wave velocity in ODP Site 893 cores. Scientific Results of the Ocean Drilling Program, V. 146.

Stoll, R.D., E. Bautista and R. Flood 1994. New tools for studying seafloor geotechnical and geoacoustic properties. Jour. Acoust. Soc. Am, 96(5), p. 2937, Nov. 1994.

Tang, D. Submitted. Modeling high-frequency acoustic backscattering from gas void buried in sediments. Geo-Marine Letters.

Tang, D., G. Jin, D. Jackson and K. Williams 1994. Analyses of high-frequency bottom and sub-bottom backscattering for two distinct shallow water environments. J. Acous. Soc. Am. 96(5), p. 2930, Nov. 1994.

Tooma, S., M. Richardson, D. Lavoie, D. Lott, K. Williams, and I. Stender. In press. The Key West Campaign: University and government laboratories try to improve technologies for the Navy's mine countermeasures system. Sea Technology (June 1995)

SYMPOSIUM PROCEEDINGS

Abegg, F. and A.L. Anderson. 1994. The acoustic turbid layer in soft mud: Methane concentration, saturation and bubble characteristics. Examples from Eckernfoerde Bay, Germany. In: Proceedings of the Third International Conference Gas in Marine Sediments, September 25-28, Texel, The Netherlands.

Abegg, F., A. Anderson, L. Buzi, A.P. Lyons, T.H Orsi. 1994. Free methane concentration and bubble characteristics in Eckernförde Bay, (pps. 84-89). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Abegg, F. and R. Koster. 1994. A simple model for the calculation of the methane saturation limit in the seafloor, (pps 108-109). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Abegg, F., A.L. Anderson, A.P. Lyons, T.H. Orsi and L. Buzi. 1995. Gas concentration and bubble distribution in the floor of Eckernförde Bay: Ground truth from core sample measurements. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Abegg, F., R. Koster and H. Rijnberg. 1995. Considerations on methane in marine mud. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Abegg, F. and A.L. Anderson. Submitted. The acoustic turbid layer in soft mud: Methane concentration, saturation and bubble characteristics: Examples from Eckerförde Bay, Germany. In: Proceedings of the Third Shallow Gas Group Meeting, Texel, The Netherlands.

Anderson, A.L., A.P. Lyons, L. Buzi, F. Abegg and T. Orsi. 1994. Modeling acoustic interaction with a gassy seafloor including examples from Eckernförde Bay, (pps 90-94). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Anderson, A.L., A.P. Lyons, T. Orsi and L. Buzi. 1995. Modeling acoustic scattering from a bubbly mud seafloor with examples from Eckernforde Bay. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Bennett, R.H., M.M. Meyer, D.M. Lavoie, M.H. Hulbert, S. Stewart and E. Littman. 1994. Sediment pore pressure and permeability in Eckernforde Bay, Germany, (pps 65-69). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Bentley, S.J., C.A. Nittrouer, G.R. Lopez. 1995. Measurement of progressive bioturbation in event layers, Eckernforde Bay. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments in Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Boyle, F.A. and N.P. Chotiros. 1994. A model for bistatic scattering trapped gas bubbles in sandy sediment. Proceedings of the Underwater Acoustic Scattering, December 20-22, Weymouth, United Kingdom, 24 pps.

Brandes, H.G. and A.J. Silva. 1995. Strength properties of pressurized and gassy sediments from Eckernforde Bay. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Briggs, K.B and M.D. Richardson. 1994. Geoacoustic and physical properties of near surface sediments in Eckernfoerde Bay, (pps 39-46). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Briggs, K.B. and M.D. Richardson. 1995. Physical property variability in sediments of Eckernforde Bay. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Bryant, W.R., N.C. Slowey and D.N. Lambert. 1995. Geotechnical stratigraphy of Eckernforde Bay, southwestern Baltic Sea. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Bussman, I., E. Suess, P. Link and M. Schluter. 1994. Seasonal transport of methane and fresh water for an active vent at Mittlegrund (Eckernförde Bay), (pps 31-32). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Chotiros, N.P. 1994. Ocean bottom acoustic interactions in MCM. Proceedings of IEEE-OES OCEANS 94, Brest, France, September 13-16, 1994, Vol. II:250-254.

Chotiros, N.P. 1994. Inversion and sandy ocean sediments. NATO Conference on Full Field Inversion Methods, 27 June - 1 July 1995, SACLANT, Italy.

Chotiros, N.P. 1995. Acoustic sediment penetration measurement with a buried hydrophone array in Eckerförde Bay. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Caruthers, J.W., E.J. Yoerge and J.C. Norvarini. 1994. High-frequency, shallow water acoustic bottom forward scatter: Measurement and model comparisons, (pps. 251-263) In: Proceedings of The Technical Cooperation Program, Subgroup G - Undersea Warfare, Heriot-Watt University, Edinburgh, Scotland, 11-15 July 1994.

D'Andrea, A.F., G.R. Lopez, C.A. Nittrouer, L.D. Wright. 1995. Fecal pellets of Abra alba as traces of sediment movement in Eckernforde Bay. In: Wever, T.F. (ed), Proceedings of

Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Davis, A.M., R. Haynes and D.G. Huws. 1994. Geophysical approaches to determining the geotechnical characteristics of seafloor sediments: Acquisition and analysis of shear wave, electrical resistivity and digital seismic sub-bottom profiler data, (pps 59-64). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Haynes, R. and A. Davis. 1995. Using seismic reflection attributes to resolve subsurface sediment characteristics. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Huws, D., A. Davis and J. Pyrah. 1995. Using shear wave velocity and electrical resistivity to resolve the spatial variability of sea floor sediment properties in Eckernforde Bay. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Davis, K.S., W.R. Bryant, N.C. Slowey and D.N. Lambert. 1994. Reflections on the geoacoustic and geotechnical characteristics in Eckernfoerde Bay Sediments, (pps 47-53). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Faas, R.W. and S. Wartel. 1995. Relationships between sediment textural properties and rheological behavior patters: Examples from Eckernforde Bay and Kiel Harbor (Baltic Sea), Germany. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Fechner, G., I.H. Stender and R. Thiele. 1994. Measurements of relative bottom backscattering strength by a digital side scan sonar in Eckernförde Bay, Baltic Sea, (pps 95-100). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Fiedler, H.M. and I.H. Stender. 1994. The Absorption layer in the Eckernfoerde Bay, (19-23). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Fiedler, H.M. 1995. The absorption layer in Eckernforde Bay sediments - an update. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Freidrichs, D.T., L.D. Wright and B.O. Kim. 1995. Sensitivity of bottom stress measurements to stratification, fluid acceleration and instrument setting Eckernforde Bay, Southern Baltic Sea. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Gilbert, K. and T. Kulbago. 1995. The Bragg conditions limitation on inversion of normal incidence reflection data. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Hawkins, J.A., D.N. Lambert, D.J. Walter and J.C. Cranford. 1994. Acoustic imaging of near-surface bubbly sediments, (pps 54-58). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Hawkins, J.A., A. Lyons, M. Duncan and A.L. Anderson. 1995. Spectral characterization of bubbly sediments using high frequency short duration acoustic pulses. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Holyer, R. 1995. Density structure of Eckernforde Bay sediments derived by image analysis: Relationships with sediment properties. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Kolle, J.J., A.C. Mueller and J. Dvorkin. 1995. Microstructural modelling of clay sediments of Eckernforde Bay. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Lambert, D.N., D.J. Walter, D.C. Young, M.D. Richardson and J.C. Cranford. 1994. High-resolution acoustic seafloor classification system for mine countermeasures operations, (pps. 67-69). In: Proceedings of International Conference on Underwater Acoustics, University of New South Wales, Australian Acoustical Society, Darlinghurst, Australia.

Lambert, D.N., D. Walter, J. Hawkins and C. Cranford. 1995. Delineation of shallow, subbottom gas concentrations using a narrow beam, high frequency acoustic system. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Lavoie, Dennis, Dawn Lavoie, Richard Bennett and Alan Pittenger. 1994. Microfabric predictors of sediment properties, (pps 70-75). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Lavoie, D. and D. Lavoie. 1995. Physical properties and microfabric from concurrent sampling across Eckernforde Bay. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Lopez, G.R., A.F. D'Andrea, N.I. Craig, S.J. Bentley, C.A. Nittrouer. 1995. Benthic macrofauna and bioturbation in Eckerforde Bay. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Lyons, A.P., A.L. Anderson and T.H. Orsi. 1994. Modeling acoustic volume backscatter from two shallow-water marine environments by side-scan sonar. Proceedings of IEEE-OES OCEANS 94, Brest, France, Vol I:862-865.

Martens, C.S., D.B. Albert and G.B. Avery. 1994. Controls on the stable isotopic composition of methane in rapidly accumulating coastal sediments. Proceedings of the Third International Conference on Gas in Marine Sediments, Texel, Netherlands.

Martens, C. and D. Albert. 1994. Biogeochemical processes controlling gas production, consumption and transport of organic-rich marine sediments, (pps 101-107). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Meyer, M., K. McCrocklin, R. Bennett. 1995. Free gas content profiel of Eckernforde Bay sediments determined by volumetric measurements. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Nittrouer, C.A., S.J. Bentley, G.R. Lopez, L.D. Wright. 1995. Observations of sedimentary character and their relationship to environmental processes in Eckernforde Bay. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Orsi, T.H., A.L. Anderson and A.P. Lyons. 1994. Geoacoustic characterization of shallow-water marine sediments for high-frequency applications, Proceedings of IEEE-OES OCEANS 94, Brest, France, Vol I:866-871.

Orsi, T.H. and A.L. Anderson. 1993. Computer tomography of biological structures in marine sediments. IEEE OCEANS 93, Victoria, Canada, September 1993.

Priebe, R., N.P. Chotiros, D.J. Walter and D.N. Lambert. 1995. Gas bubble recognition by wavelet analysis of echo-sounder signals. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Richardson, M.D. 1994. The Coastal Benthic Boundary Layer Special Research Program: The Eckernfoerde experiments, (pps 3-10). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Richardson, M.D., S.R. Griffin and F.B. Grosz. 1994. ISSAMS: An in-situ sediment acoustic measurement system. (pps. 104-106). In: International Conference on Underwater Acoustics, University of New South Wales, Australian Acoustical Society, Darlinghurst, Australia.

Richardson, M.D., D.N. Lambert, K.B. Briggs and D.J. Walter. 1994. Comparison of Acoustic Seafloor Classification (ASCS) and In-Situ Geoacoustic (ISSAMS) data collected from a variety

of sediment types in Kiel Bay, Germany, (pps. 89-90). In: International Conference on Underwater Acoustics, University of New South Wales, Sydney, Australian Acoustical Society, Darlinghurst, Australia.

Richardson, M.D. 1995. Geoacoustic properties of Eckernforde Bay. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Sadd, M.H., A. Shukla, F. Sienkiewicz, and A. Gautam. 1994. On the role of pore fluid and inter-particle cementation on wave propagation in granular material. Symposium on Wave Propagation and Emerging Technologies, 1994 ASME Winter Annual Meeting Nov 6-11. 1994.

Silva, A.J., H.G. Brandes, G.E. Veyera. 1995. Geotechnical properties and behavior of organic gassy sediments in Eckernforde Bay, Baltic Sea. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Silva, A.J., H.G. Brandes, A. Ag, D. Brogan. 1995. Compressibility, permeability, and strength properties of Eckernforde Bay sediments. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Stender, I.H. and G. Fechner. 1995. Relative backscattering strength from side-scan sonar data. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Stanic, S., R. Goodman, E. Kennedy and R. Smith. 1995. High-frequency reverberation from muddy sediments. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Stanic, S., E. Kennedy, R. Smith and N. Chotiros. 1995. High-frequency acoustic penetration in gassy sediments. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Stoll, R.D., and T. Akal. 1994. Experimental techniques for bottom parameter inversion in shallow water. Proceedings NATO Conference Full Field Inversion Methods in Ocean and Seismic Acoustics" edited by Diachok, O., Caiti, A., Gerstoft, P., and Schmidt, H. (Kluwer, Dordrecht).

Stoll, R.D. and F. Bautista. 1995. Measuring near-bottom shear wave velocity using Love waves. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Tang. D., C.S. Sellers, G.V. Frisk and S.G. Schock. 1995. High-frequency acoustic scattering from the gassy sediment in Eckernforde Bay. In: Wever, T.F. (ed), Proceedings of Modelling

Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Tooma, S.G., and M.D. Richardson. 1994. Contributions of the Naval Research Laboratory Geosciences Program to mine countermeasures, (pps. 221-232). In: Proceedings of The Technical Cooperation Program, Subgroup G - Undersea Warfare, Heriot-Watt University, Edinburgh, Scotland, 11-15 July 1994.

Wever, F., H.M. Fiedler and I.H. Stender. 1995. The acoustic turbidity: Its variation in depth and time. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Wilkens, R.H. and S.S. Fu. 1994. Acoustic Lance operations in Eckernforde Bay, 1994, (pps. 34-38). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

Williams, K., P. Dahl, and D. Jackson. 1994. Some current efforts and future plans in surface and bottom scattering characterization, (pps. 267-276). In: Proceedings of The Technical Cooperation Program, Subgroup G - Undersea Warfare, Heriot-Watt University, Edinburgh, Scotland, 11-15 July 1994.

Williams, K., and D. Jackson. 1994. Monostatic and bistatic bottom scattering: recent experiments and modeling. Proceedings of IEEE-OES OCEANS 94, Brest, France, September 13-16, 1994, Vol II:255-260.

Williams, K. and D.R. Jackson. 1995. Acoustic scattering measurements at 40 kHz. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Wilson, M.A., R.W. Farwell and S. Stanic. 1994. High-frequency propagation statistics in a shallow water environment. Proceedings of IEEE-OES OCEANS 94, Brest, France, September 13-16, 1994, Vol II:261-265.

Wright, L.D. and C.T. Freidrichs. 1995. Physical processes of sediment transport and accumulation in Eckernforde Bay. In: Wever, T.F. (ed), Proceedings of Modelling Methane-Rich Sediments at Eckerförde Bay, held at Eckernförde, Germany, 26-30 June 1995, in press.

Young, D. K., R. Holyer and J.C. Sandidge. 1994. Texture of Sediments from Eckernfoerde Bay: An Image Analysis Approach, (pps 76-83). In: Wever, T.F. (ed.), Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, Germany, 11-12 July 1994.

TECHNICAL REPORTS

Abegg, F. 1992. Report for FWG: Final report for the Research Contract "Investigation of Gas Content and Conductivity of Marine Sediments," Interval 1989-1992, 92 pps, Geol.-Paläont. Inst. Univ. Kiel.

Abegg, F. 1993. Report for FWG, Interim Report 1 for the Interval 01.02. - 30.06.1993, 9 pps. Geol.-Paläont. Inst. Univ. Kiel.

Abegg, F. 1993. Report for FWG, Interim Report 2 for the Interval 01.07. - 31.12.1993, 52 pps. Geol.-Paläont. Inst. Univ. Kiel.

Abegg, F. 1993. Report for FWG, Interim Report 3 for the Interval 01.01. - 30.06.1994, 9 pps. Geol.-Paläont. Inst. Univ. Kiel.

Abegg, F. 1993. Investigation regarding the influence of sedimentological and geochemical values on the acoustic behaviour of the seafloor, (in German). Abschlussbricht zum Forschungsvertag T/RF 35/F 0018/F 1310:92 pages. Geol.-Paläont. Inst. Univ. Kiel.

Abegg, F. 1994. Report for FWG, Final Report for Interval 01.02.1993 - 31.12.1994, 60 pps. Geol.-Paläont. Inst. Univ. Kiel.

Abegg, F. 1995. Report for FWG, Interim Report 1 for the Interval 01.01.1995 - 31.03.1995, 5 pps. Geol.-Paläont. Inst. Univ. Kiel.

Abegg, F. 1995. Untersuchung des Einflusses sedimentologischer und geochemicher Parameter auf die akustischen Eigenschaften des Meeresbodens il. Technical Report E/S41C/P0093/N503. Geol.-Paläont. Inst. Univ. Kiel, 5 pps.

Abegg, F. 1995. Investigations concerning the influence of sedimentological and geochemical values on seafloor acoustic behavior of the seafloor (in German). Abschlussbericht zum Forschungsyertrag E/S41C/N0059/N5203. Geol.-Paläont. Inst. Univ. Kiel, 66 pps.

Bennett, R.H., W.A. Dunlap and H.J. Lee. 1991. Seabed interaction. Workshop report and recommendations for future research, Metairie, LA, November 5-6, 1991.

Dahl, P.H., D.R. Jackson and K.L. Williams. 1995. The TEVA experiment cruise report. Applied Physics Laboratory, University of Washington, March 1995, 15 pps.

Fiedler H.M., I. H. Stender. 1995. Surveying of sediment distribution and depth of the gassy absorption layer with side scan sonar and subbottom profiler at Eckernforde Bay, Baltic Sea. FWG Report 18, Kiel, February 1995.

Fischer, K., and C. Farno. 1993. Sediment geochemical processes: Field participation at Eckernfoerde Site (Coastal Benthic Boundary Layer Special Research Project, NRL Memo Report NRL/MR/7432--93-7076, NRLSSC.

Fiedler, H. and I. Stender 1993. Surveying of sediment distribution and depth of the gassy absorption layer with side scan sonar and subbottom profiler at Eckernfoerde Bay, Baltic Sea, FWG Technical Report TB 1993-18, FWG, Germany, 17 pps.

Gilbert, G.D. 1992. Coastal warfare optics and electromagnetics a workshop on research needs and opportunities for the changing world, 2 Aug 92.

Goodman, R.A., A.L. Anderson, D.R. Jackson, J.B. Mooney, T.G. Muir, M.D. Richardson, and F.G. West. 1994. Environmental parameters, Chapter 4, Volume II. In Mine Countermeasures Technology Study. L. Hunt, ed. Naval Studies Board, National Academy of Sciences, National Academy Press, Washington, DC.

Jackson, D.R. and P.A. Jumars. 1992. Interactions between environmental processes at the seabed and high-frequency acoustics: Workshop recommendations, 4 Mar 92.

Muir, T.G. and C.S. Clay. 1992. Proceedings of the ONR Workshop on Sediment Classification for the Special Research Program on the Coastal Benthic Boundary Layer.

Orsi, T.H., A.L. Anderson, K.M. Fischer, K.S. Davis, W.R. Bryant, R. Rezak, C. Brunner and A. Falster. 1995. Computed tomography and geoacoustic properties of carbonate muds from Marquesas Keys and Dry Tortugas, south Florida. NRL Report, in press.

Richardson, M. D. 1992. Coastal Benthic Boundary Layer SRP, BAA 92-3, NRL, SSC, MS.

Richardson, M. 1992. Coastal Benthic Boundary Layer Special Research Program: Program Direction and Workshop Recommendations, Naval Research Laboratory, SSC, MS Special Report SP 017:361:92.

Richardson, M. 1992. Coastal Benthic Boundary Layer Special Research Program: A Review of the First Year, Volume I. Naval Research Laboratory, SSC, MS Memo Report NRL/MR/7431--94-7099.

Richardson, M. 1995. Coastal Benthic Boundary Layer Program. NRL Review, NRL (in press).

Richardson, M. 1995. Coastal Benthic Boundary Layer: A Review of the Second Year. Naval Research Laboratory, SSC, MS Memo Report NNR/MR/7431--95- , in press

Wever, T. 1993. Research Cruise with WFS PLANET 29.3. - 6.4.1993 (Cruise Report), FWG Technical Report TB 1993-5, FWG, Germany, Nov. 93.

Wever, T. 1994. Proceedings of the Gassy Mud Workshop held at the FWG, Kiel, 11-12 July, 1994. FWG Report 14:114pps.

Wever, T. 1994. Zür Löslichkeit von Methan in marinen Sedimenten. FWG Report 16:18pps.

PUBLISHED ABSTRACTS

Abegg, F., and R. Koster. 1994. Methane determination in soft marine sediments from the german parts of the Baltic and North Sea. EOS, 75(3):159.

Albert, D.B., and C.S. Martens. 1994. Biogeochemical processes in surficial sediments of Eckernfoerde Bay, EOS, 75(3):159.

Anderson, A.L. and F. Abegg. 1994. Measurement of gas bubble concentration and distribution in the seafloor at Eckernfoerde Bay, Germany. EOS, 75(3):159.

Bennett, R.H., D. Lavoie, M. Meyer, E. Litman, and S. Stewart. 1994. Pore pressure field in Eckernforde Bay, Germany. EOS, 75(3):201.

Bowman, L. and H. Hermann. 1995. Spatial variability of strength properties of offshore carbonate sediments in three environments. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Boyle, F.A. and N.P. Chotiros. 1994. A model for bistatic scattering from trapped gas bubbles in sandy sediments. Underwater Acoustic Scattering, Weymouth, UK, 20-22 December. 1994.

Brandes, H.G. and A.J. Silva. 1994. Acoustical properties of undisturbed sands from the west Florida sand sheet, J. Acoust. Soc. Am., 96(5):3246.

Brandes, H.G., G.E. Veyera and A.J. Silva. 1994. Rheological characteristics of high porosity surficial sediments at the CBBL/SRP Baltic Sea site. EOS, 75(3):202.

Briggs, K.B. 1994. Correlation functions for sediment acoustic properties. J. Acoust. Soc. Am., 96(5):3245-6.

Briggs, K.B., M.D. Richardson and D.R. Jackson. 1994. High-frequency bottom backscattering: volume scattering from gassy mud. J. Acoust. Soc. Am., 96(5):3218.

Briggs, K.B., M.D. Richardson, and D.B. Percival. 1994. Correlation functions estimated from vertical profiles of sediment porosity and compressional wave velocity fluctuations. EOS, 75(3):202.

Briggs, K.B. and M.D. Richardson. 1995. Geoacoustic and physical properties of carbonate sediments from the Key West Campaign. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Brown, R., E. Besancon, and R. Smith. 1994. Acoustic high-frequency processing: a compilation of environmental data from Eckernfoerde Bucht, Germany and the upper Gulf of Mexico near Panama City, Florida. EOS, 75(3):221.

Bryant, W.R. and A. Anderson. 1994. Gassy marine sediments. presented at the Third International Conference on Gas in Marine Sediments, Texel, The Netherlands, September 25-28. 1994.

Bryant, W.R. and N.C. Slowey. 1994. The geoacoustic and geotechnical properties of Eckernfoerde Bay. EOS, 75(3):220.

Bryant, W., N. Slowey and D. Lambert. 1995. Geotechnical and geoacoustics stratigraphy of the Dry Tortugas. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Chotiros, N.P., R.A. Altenberg, and S.J. Stanic. 1994. High frequency acoustic penetration of ocean sediments. J. Acoust. Soc. Am., 96(5):3265.

Chotiros, N., R.A. Altenburg and F.A. Boyle. 1994. Reflection coefficient of sandy ocean sediments in shallow water. EOS, 75(3):181.

Davis, A., D. Huws and R. Haynes. 1994. Geophysical ground-truthing experiments in Eckernfoerde Bay. J. Acoust. Soc. Am., 96(5):3218.

Davis, A., D. Huws, R. Haynes and J. Bennell. 1995. Geophysical sea floor sensing in a carbonate sediment regime. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

DeBruin, D.L., LeBlanc, L.R., and S.G. Schock. 1994. Correlation of acoustic impedance and volume scattering with sediment mean grain size and bulk density. J. Acoust. Soc. Am., 96(5):3223.

Faas, R.W. 1994. Viscoelastic properties of Eckernfoerde Muds. EOS, 75(3):180-1.

Faas, R. and T. Orsi. 1995. Rheological properties of carbonate sediments. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Fechner, G. and I.H. Stender. 1994. Measurements of relative bottom backscattering strength by a digital side scan sonar. J. Acoust. Soc. Am., 96(5)3222-3.

Fiedler, H., T. Wever and I Stender. 1995. SSS images of the seafloor of the dry tortugas. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Fielder, H.M. and I.H. Stender. 1994. Surveying sediment distribution and depth of the gassy absorption layer with side scan sonar and subbottom profiler at Eckernfoerde Bay, Germany. EOS, 75(3):159.

Fischer, K.M. and T.H. Orsi. 1994. Porosity gradients in Eckernfoerde Bay (Baltic Sea), Germany: Organic carbon content microstructural, textural and clay mineralogical effects. EOS, 75(3):220.

Fleischer, P., W.B. Sawyer, H. Fielder, and I. Stender. 1994. Spatial and temporal complexity on a simple, sandy inner-shelf seafloor: Observations with Side Scan Sonar. EOS, 75(3):220.

Flint, R.F., P.D. Jackson, M.A. Lovell, and P.K. Harvey. 1994. Micro-resistivity imaging of very high porosity sediments: an aid to the evaluation of heterogeneity. EOS, 75(3):201.

Furukawa, Y., D. Lavoie and D. Wiesenburg. 1995. Oxidation of aqueous sulfide in porewater as the possible cause for carbonate dissolution during early diagenesis. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Gilbert, K.E. and T.L. Kulbago. 1994. A numerical study of normal incidence acoustic backscatter from gassy sediments. EOS, 75(3):160.

Gilbert, K., T. Kulbago and P. White. 1994. A structure function constraint for stable least-squares inversion of reflection data. J. Acoust. Soc. Am., 96(5):3224.

Gilbert, K.E. and T.J. Kulbago. 1995. The Bragg condition limitation of inversion of normal incidence reflection data. J. Acoust. Soc. Am., in press.

Hawkins, J.A., D.N. Lambert, D.J. Walter, and J.C. Cranford. 1994. Observations of acoustic reflectivity associated with near surface (shallow subbottom) gassy sediments in Kiel and Eckernfoerde Bays. EOS. 75(3):159.

Hawkins, J.A., W.T. Wood, D.N. Lambert and D.J. Walter. 1994. The characterization of near-surface sediments with high frequency acoustic pulses. J. Acoust. Soc. Am., 96(5):3223.

Holyer, R.J., D.K. Young, J.R. Chase and K.B. Briggs. 1994. Sediment density structure inferred by textural analysis of cross-sectional x-radiographs and electron microscopy images. EOS, 75(3):202.

Hunt, P.H. and S.T. Inkpen. 1994. Real time digital imaging of quaternary sediments off Panama City, Florida. EOS, 75(3):220.

Jackson, D. and L.D. Wright. 1994. Influence of sediment transport events upon bottom backscattering, Eckernfoerde Bay. J. Acoust. Soc. Am., 96(5):3247.

Jackson, D.R. and K.L. Williams. 1994. Acoustic observations of benthic variability and time evolution. EOS, 75(3):181.

Jackson, P.D., K.B. Briggs, R.F. Flint, M.A. Lovell and P.K. Harvey. 1994. Evaluation of the porosity structure of coastal benthic boundary layer sediments using micro-resistivity imaging. EOS, 75(3):201.

Jackson, P.D., K.B. Briggs, R.F. Flint, M.A. Lovell and P.K. Harvey. 1994. The investigation of millimetre scale heterogeneity in coastal benthic boundary layer sediments using micro-resistivity and x-ray imaging of 'diver' cores. J. Acoust. Soc. Am., 96(5):3245.

Jumars, P. and D. Jackson. 1994. Acoustic backscatter as a means of assessing benthic biological activity over a broad range of scales. EOS, 75(3):181.

Kolle, J.J., A.C. Mueller, and J. Dvorkin. 1994. microstructural modeling of clay sediments in eckernfoerde bay. J. Acoust. Soc. Am., 96(5):3246.

Kolle, J.J. 1994. Structural analysis of marine sediment microfabric to derive biot poroelasticity constants. EOS, 75(3):202.

Kulbago, Timothy J. and Kenneth E. Gilbert. 1994. Inversion of normal incidence backscatter data from gassy sediments. J. Acoust. Soc. Am., 95(5):3018.

Lambert, D.G., D.J. Walter, W.R. Bryant, N.C. Slowey and J.C. Cranford. 1994. Acoustic prediction of sediment impedance. J. Acoust. Soc. Am., 96(5)3222.

Lambert, D.N., J.C. Cranford, D.J. Walter, J.A. Hawkins and R.D. Redell. 1994. Geological characterization of Kiel and Eckernfoerde bay sediments using a high resolution remote Acoustic Seafloor Classification System. EOS, 75(3):160.

Lambert D.N., D.J. Walter, J.C. Cranford, and D.C. Young 1994. Use of a high resolution, high-frequency, normal incidence seafloor classification system for mine countermeasures operations, (p.113). In: Proceedings of The Technical Cooperation Program, Subgroup G - Undersea Warfare, Heriot-Watt University, Edinburgh, Scotland, 11-15 July 1994.

Lavoie, Dawn and H. Alan Pittenger. 1994. In situ measurement of shear modulus using DIAS. EOS, 75(3):160.

Lavoie, Dennis, R.H. Bennett, W. Chiou, R.J. Baerwald, and M.H. Hulbert. 1994. Sediment microfabric of gassy sediments in Eckernfoerde Bay. EOS, 75(3):201.

Lavoie, D. and D. Lavoie. 1995. Relationship between geotechnical properties and microfabric in florida carbonate sediments. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Lopez, G.R., N.I. Craig, and W.G. Wallace. 1994. Benthic faunal distribution and sediment bioturbation in Eckernfoerde Bay. EOS, 75(3):180.

Lyons, A.P., A.L. Anderson, and T.H. Orsi. 1994. Estimates of volume scattering cross section and related parameters due to property variability in Eckernfoerde Bay. EOS, 75(3):203.

Lyons, A.P., M.E. Duncan, James A. Hawkins, Jr. and A.L. Anderson. 1994. Predictions of the acoustic response of free methane bubbles in muddy sediments. J. Acoust. Soc. Am., 96(5):3217.

Lyons, A.P. and T.H. Orsi. 1994. Characterization of seafloor property variability and estimates of acoustic volume scattering cross section in Eckernfoerde Bay, Germany. presented at the 6th Annual Student Symposium, College of Geosciences and Maritime Studies/Ocean Drilling Program, Texas A&M University, College Station, TX, February 19. 1994.

Mallinson, D., M. Hafen, Y. Rappaport, D. Naar, A. Hine, D. Lavoie and S. Schock. 1995. Preliminary results from a high resolution geophysical investigation of a mixed carbonate-siliciclastic nearshore environment off Boca Raton, Florida. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Martens, C.S., D.B. Albert, H. Fiedler, and F. Abegg. 1994. Biogeochemical processes controlling gas bubble production and distribution in organic-rich sediments. J. Acoust. Soc. Am., 96(5):3217.

Mire, C.T. and S. Stanic. 1994. Acoustic phase stability in a shallow water environment. J. Acoust. Soc. Am., 96(5):3286.

Nittrouer, C.A., C.K. Sommerfield and S.J. Bentley. 1994. Formation of sedimentary strata in Eckerfoerde Bay (Baltic Sea). EOS, 75(3):180.

Orsi, T.H. 1994. Computed tomography of macrostructure and physical property heterogeneity in surface sediments of Eckernfoerde Bay (Western Baltic Sea). Presented at the 6th Annual Student Symposium, College of Geosciences and Maritime Studies/Ocean Drilling Program, Texas A&M University, College Station, TX, February 19. 1994.

Orsi, T.H. 1994. A method for quantifying bubble characteristics in gassy aqeous sediments. Presented at the 6th Annual Student Symposium, College of Geosciences and Maritime Studies/Ocean Drilling Program, Texas A&M University, College Station, TX, February 19. 1994.

Orsi, T.H. and A.L. Anderson. 1994. Bubble characteristics in gassy sediments. Presented at the Gulf Coast Association of Geological Societies Convention, Austin, TX October 5-7. 1994.

Orsi, T.H. and A.L. Anderson. 1994. Macroscale heterogeneity of sediments from Eckernforde Bay (Western Baltic Sea): Quantitative Characterization using X-Ray CT. EOS, 75(3):220.

Orsi, T.H, A.L. Anderson, W.R. Bryant, K. Davis, R. Rezak and N. Slowey. 1995. Computed tomography of macroscale heterogeneity of carbonate muds, Marquesas Keys and Dry Tortugas,

South Florida. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Orsi, T.H., A.L. Anderson, W.R. Bryant, K. Davis, R. Rezak and N. Slowey. 1995. Physical property gradients in carbonate muds of the Florida Keys. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Richardson, M.D. 1992. Coastal Benthic Boundary Layer Special Research Program. J. Acous. Soc, Am., 92:2308

Richardson, M.D., S.R. Griffin, K.B. Briggs, A.L. Anderson and A.P. Lyons. 1994. The effects of free methane bubbles on the propagation and scattering of compressional and shear wave energy in muddy sediments. J. Acoust. Soc. Am., 96(5):3218.

Richardson, M.D. 1994. The Coastal Benthic Boundary Layer Special Research Project: A Review of the First Year. EOS 75(3):159.

Richardson, M.D., S.R. Griffin and K.B. Briggs. 1994. In-situ sediment geoacoustic properties: a comparison of soft mud and hard packed sand sediments. EOS, 75(3):220.

Richardson, M.D. 1995. The Coastal Benthic Boundary Layer. Annales Geophysicae, Vol. 13(II):C247.

Richardson, M.D. and S.R. Griffin. 1995. Geoacoustic properties of carbonate sediments. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Sadd, M.H., A. Gautam, A.J. Silva and G.E. Veyera. 1994. A propagation model for wave motion in saturated granular sediments. presented at J. Acoust. Soc. Am., 96(5):3246.

Sadd, M.H., Q.M. Tai, A.J. Silva and G.E. Veyera. 1994. Discrete element microstructural modeling of geoacoustic wave propagation in saturated granular seabed sediments. EOS, 75(3):202.

Schock, S.G. and L.R. LeBlanc. 1994. Analysis of wideband fm subbottom data from Kiel Bay, Germany. EOS, 75(3):160.

Schock, S.G. and L.R. LeBlanc. 1994. FM sonar characteristics for normal incidence sediment classification. J. Acoust. Soc. Am., 96(5):3222.

Shiller, A.M., T.L. Hebert, K.R. Thornton and C.A. Brunner. 1995. Sediment chemistry and pore water fluxes in the vicinity of the Dry Tortugas. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Silva, A.J., H.G. Brandes and G.E. Veyera. 1994. Variability of geotechnical properties of high porosity surficial sediments at the CBBL/SRP Baltic Sea Site. EOS, 75(3):202.

Silva, A.J., H.G. Brandes, A. Ag, D. Brogan, P. Pizzimenti and G. Veyera. 1995. Geotechnical and acoustical properties of calcareous sediments at the Dry Tortugas and Marquesas CBBL sites. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Slowey, N.C., W.R. Bryant and D.N. Lambert. 1994. The geoacoustic and geotechnical properties of Eckernfoerde Bay. Presented at the Third International Conference on Gas in Marine Sediments, Texel the Netherlands, September 25-28.

Stanic, S., E. Kennedy and R. Goodman. 1994. High-frequency acoustic bottom reverberation. J. Acoust. Soc. Am., 96(5):3264.

Stanic, S., E. Kennedy, R. Brown, R. Smith and E. Besancon. 1994. An overview of the high-frequency boundary scattering measurements conducted in Eckernforde Bay, Germany and Off Panama City, Florida. EOS, 75(3):181.

Stender, I.H. and G. Fechner. 1994. Spatial distribution of relative bottom backscattering strength using a digital side scan sonar at Eckernfoerde Bay, Germany. EOS, 75(3):159.

Stephens, K., D. Lavoie, Y. Furukawa and K. Briggs. 1995. Variability of physical properties from the Dry Tortugas and Marquesas Keys. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Stoll, R.D and E. Bautista. 1994. New tools for exploring near-bottom sediments. EOS, 75(3):160.

Stoll, R.D. 1994. Modeling the near-bottom seafloor. J. Acoust. Soc. Am., 96(5)3246.

Tang, D. 1994. Modeling of high-frequency acoustic wave scattering by sediment gas voids. J. Acoust. Soc. Am., 96(5):3218.

Tang, D., G. Jin, D.R. Jackson, and K.L. Williams 1994. Analysis of high-frequency bottom backscattering data obtained from two distinct shallow water environments. EOS, 75(3):181.

Veyera, G.E., A. Ag, and H.G. Brandes 1994. Compressibility and permeability behavior of high porosity surficial sediments at the CBBL/SRP Baltic Sea Site, EOS, 75(3):202.

Walter, D. and D. Lambert. 1995. Seismic description of the Dry Tortugas. SEPM Congress on Sedimentary Geology. Held in St. Petersburg, FL, 13-16 Aug. 1995, in press.

Wilson, M.A. 1995. Fluctuations of high frequency pulses in shallow water. J. Acoust. Soc. Am., in press

White, P.J., Gilbert, K.E., and R. Goodman. 1994. Laboratory measurements of variability in high-frequency bottom backscatter due to thermal fluctuations. J. Acoust. Soc. Am., 96(5):3286.

Williams, K. and D. Jackson. 1994. Bistatic Bottom Scattering at High Frequencies: Experiment and model comparison. J. Acoust. Soc. Am., 96(5):3286.

Wright, L.D. 1994. Benthic transport phenomena in Eckernfoerde Bay (Baltic Sea). EOS, 75(3):180.

Zhang, Li, R. Goodman and S. Stanic. 1994. Acoustic pulse to pulse variability due to sea water temporal temperature fluctuations. J. Acoust. Soc. Am., 96(5):3286.

THESIS, DISSERTATIONS, AWARDS, ETC.

Ag, A. 1995. Consolidation and permeability behavior of high porosity baltic sea sediments. University of Rhode Island, Master's Thesis.

Brogan, D. 1995. The strength behavior of Baltic Sea sediments. Department University of Rhode Island, Master's Thesis.

Gautam, A. 1995. Wave propagation in saturated granular materials. University of Rhode Island, Master's Thesis.

Martens, C.S. 1995. Biogeochemical processes controlling methane in the gassy sediments of Eckernförde Bay, Baltic Sea, Germany. B.H. Ketchm Award Lecture, Woods Hole Oceanographic Institution.

Orsi, T.H. 1994. Computed tomography of macrostructure and physical property variability of seafloor sediments. Ph.D. dissertation, Texas A&M University, College Station, TX, 184 pps.

☆U.S. GOVERNMENT PRINTING OFFICE: 1995 - 662-405